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CALCULATED MAXIMUM HCl GROUND-LEVEL CONCENTRATIONS DOWNWIND FROM LAUNCH PAD ABORTS OF THE SPACE SHUTTLE AND TITAN III C VEHICLES AT KENNEDY SPACE CENTER

DRA

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Marshall Space Flight Center
Alabama 35812

H. E. CRAMER COMPANY
P. O. Box 9249
Salt Lake City, Utah 84109

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FOREWORD

This report has been prepared for NASA/MSFC under Contract No. NAS8-29033. We are indebted to Dr. Leonard DeVries and Mr. John Kaufman of the Aerospace Environment Division, Aero-Astrodynamics Laboratory, Marshall Space Flight Center for their assistance in the preparation of this report. We also gratefully acknowledge the assistance of Mr. Delwin Mecham of Thiokol Chemical Corporation, Brigham City, Utah in providing us with information on the probable emissions of the solid engines of the Space Shuttle vehicle during pad-abort situations.

SUMMARY

This report describes a quantitative assessment of the potential environmental hazard posed by the atmospheric release of HCl resulting from the burning of solid propellant during two hypothetical on-pad aborts of the Titan III C and Space Shuttle vehicles at Kennedy Space Center. In one pad-abort situation, it is assumed that the cases of the two solid-propellant engines are ruptured and the burning propellant falls to the ground in the immediate vicinity of the launch pad where it continues to burn for 5 minutes. In the other pad-abort situation considered, one of the two solid engines on each vehicle is assumed to ignite and burn at the normal rate while the vehicle remains on the launch pad. Calculations of maximum HCl ground-level concentration for the above on-pad abort situations were made using the computerized NASA/MSFC multilayer diffusion models in conjunction with appropriate meteorological and source inputs. Three meteorological regimes at Kennedy Space Center are considered—fall, spring and afternoon sea-breeze. Source inputs for the hazard calculations were developed from information supplied by NASA/MSFC and by Mr. Delwin Mecham of Thiokol Chemical Corporation. The principal result of the calculations is that maximum ground-level HCl concentrations at distances greater than 1 kilometer from the launch pad are less than 3 parts per million in all cases considered.

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SECTION 1
INTRODUCTION

1.1 PURPOSE

The purpose of this technical memorandum is to present calculations of peak ground-level HCl concentrations downwind from pad aborts of the Titan III C and Space Shuttle vehicles at Cape Kennedy for three meteorological situations.

1.2 VEHICLE FUEL DATA

Basic vehicle fuel characteristics used in the calculations are given in Table 1-1. As indicated in the table, both the Space Shuttle and Titan III C zero stages are comprised of two solid-fueled rockets and the major exhaust component of interest is hydrogen chloride (HCl). Estimates in Table 1-1 of total fuel and HCl content of the engines for the Titan III C vehicle were obtained from available literature. Mr. D. Meacham of the Thiokol Chemical Corporation supplied the estimates of total fuel and HCl content of the Space Shuttle engines as well as the enthalpy data for the heat produced by the burning of the fuel.

1.3 DEFINITION OF PAD ABORT SITUATIONS

Calculations of HCl ground-level concentrations have been made for two types of on-pad abort situations. In one set of calculations—slow burn on pad—the cases of the two solid rockets of the zero stage were assumed to be ruptured by an on-pad explosion, resulting in the solid fuel from both engines burning over a 5-minute period. In the other set of calculations (single engine burn), only one solid engine of the zero stage was assumed to ignite and burn over a normal firing period, with the vehicle held on the launch pad.

TABLE 1-1

VEHICLE FUEL CHARACTERISTICS

	Titan III C	Space Shuttle
Total Fuel (lbs) (2 Engines)	1.16×10^6	2.50×10^6
Total HCl (lbs) (2 Engines)	1.76×10^5	4.95×10^5
Enthalpy (cal g^{-1})		
Slow Burn On Pad	1000	1000
Single Engine Burn	691	691

1.4 METEOROLOGICAL CONDITIONS

The three meteorological situations used in the hazard calculations are based on the mean monthly wind speed, wind direction, and temperature profiles for Kennedy Space Center (KSC) published by Smith and Vaughan (1961) and on the work of Record, et al. (1970). These profiles have been previously used in hazard calculations for launches at KSC (Dumbauld and Bjorklund, 1971; and Cramer, et al., 1972). These previous calculations show that peak ground-level concentrations are primarily dependent on the depth of the surface mixing layer H_m and the vertical distribution of material in the stabilized cloud resulting from the pad abort. Study of the meteorological profiles for KSC showed that, for easterly flow required to transport the combustion cloud inland, the average mixing depth was about 1000 meters. During the spring, however, there are a few occasions when the surface mixing depth is about 2000 meters. Also, during the afternoon sea breeze which develops in all seasons, the average surface mixing depth is about 300 meters. Composite vertical profiles of air temperature, wind direction, and wind speed for easterly wind regimes at KSC used in the hazard calculations are shown in Figures 1-1, 1-2 and 1-3. The three meteorological regimes represented are fall, spring and afternoon sea breeze.

1.5 REPORT ORGANIZATION

Section 2 below contains a brief description of the calculation of buoyant cloud rise. The meteorological diffusion model used in calculating peak ground-level concentration is discussed in Section 3. The procedures used in apportioning the HCl in the various atmospheric layers is described in Section 4 and the source and meteorological model inputs are given in Section 5. The results of the calculations are discussed in Section 6.

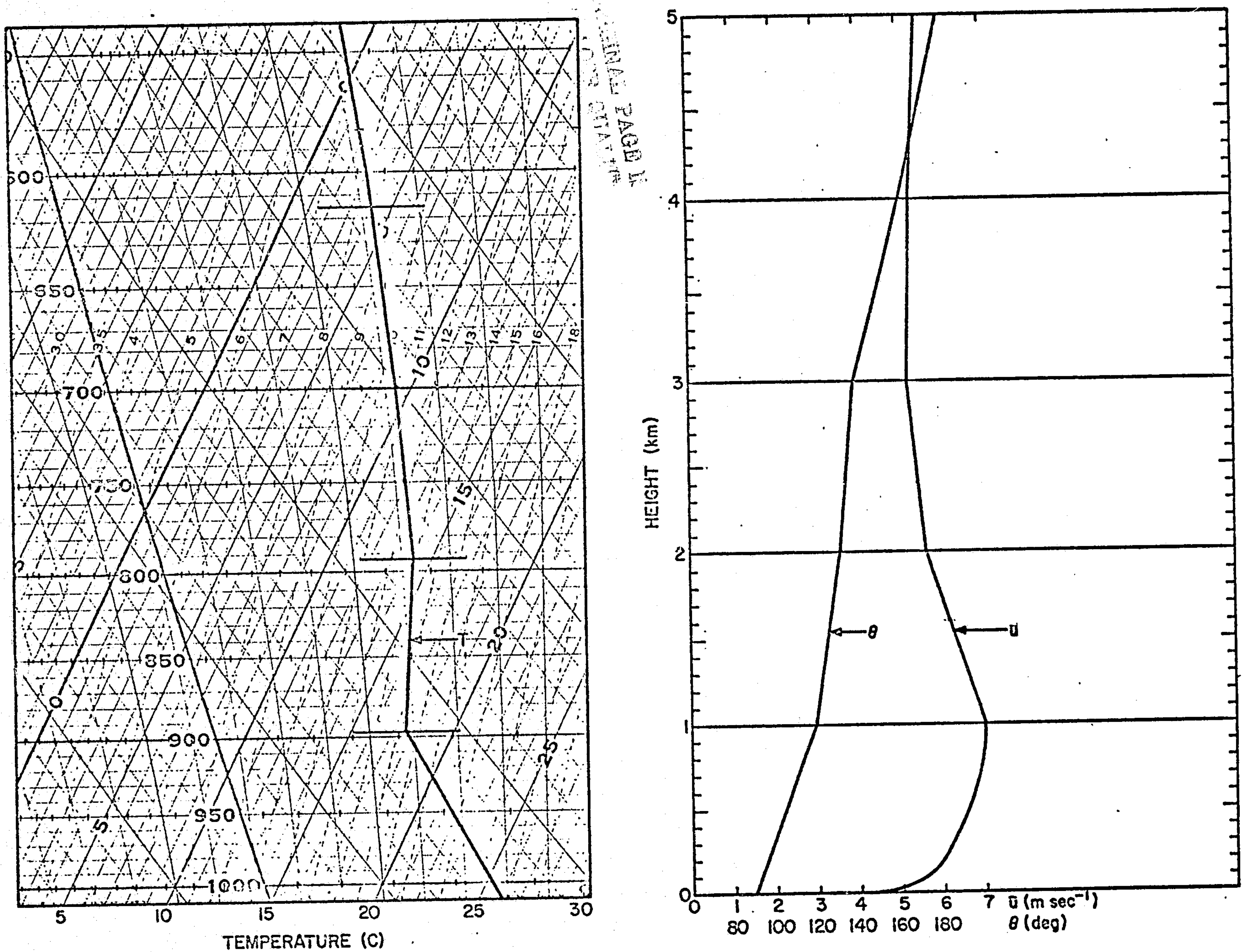

FIGURE 1-1. Vertical profiles of air temperature T, mean wind direction θ, and mean wind speed $\bar{u}$ for the fall meteorological regime at KSC. Heavy horizontal lines indicate layer boundaries.

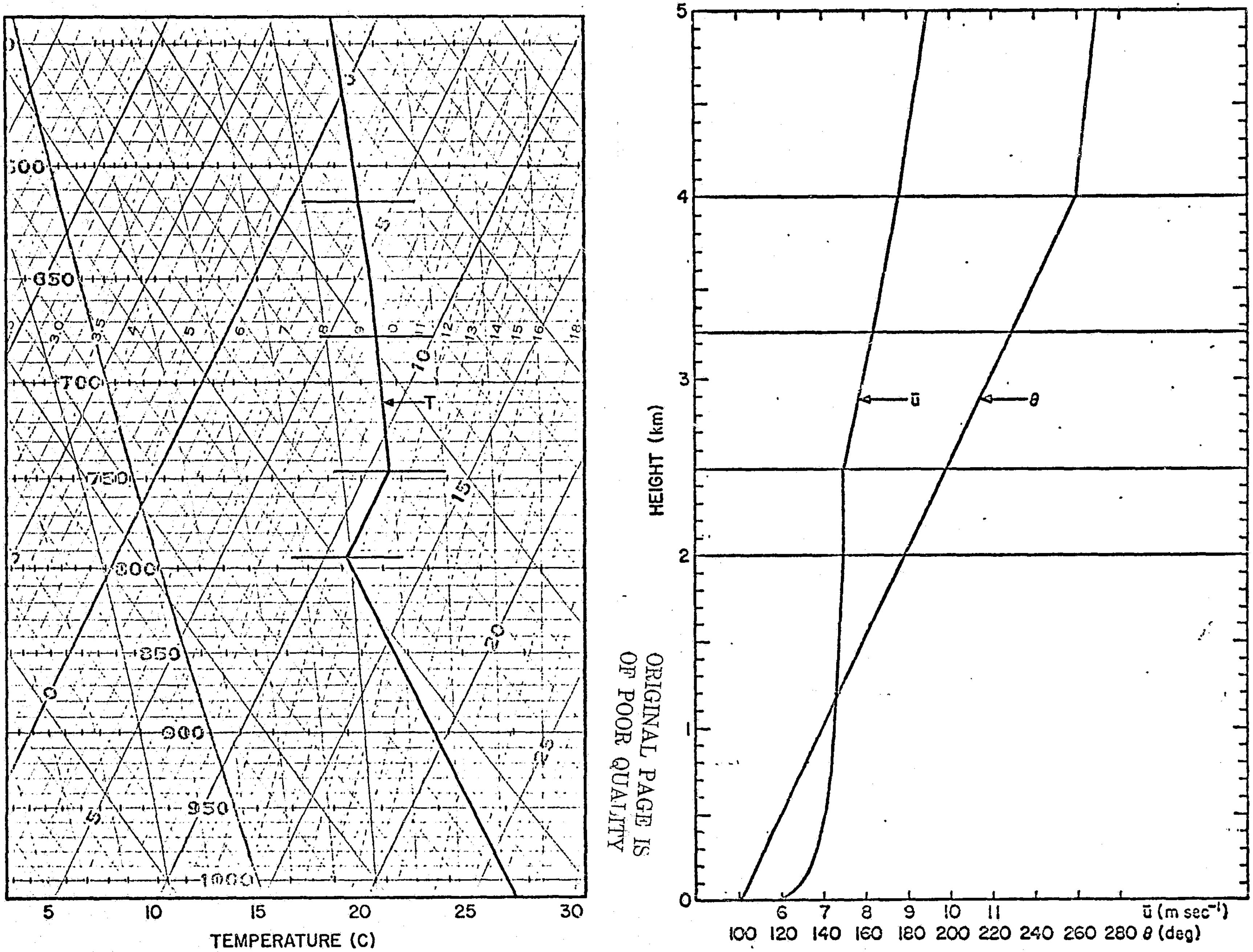

FIGURE 1-2. Vertical profiles of air temperature T, mean wind speed ū and wind direction Θ for the spring meteorological regime at KSC. Heavy horizontal lines indicate layer boundaries.

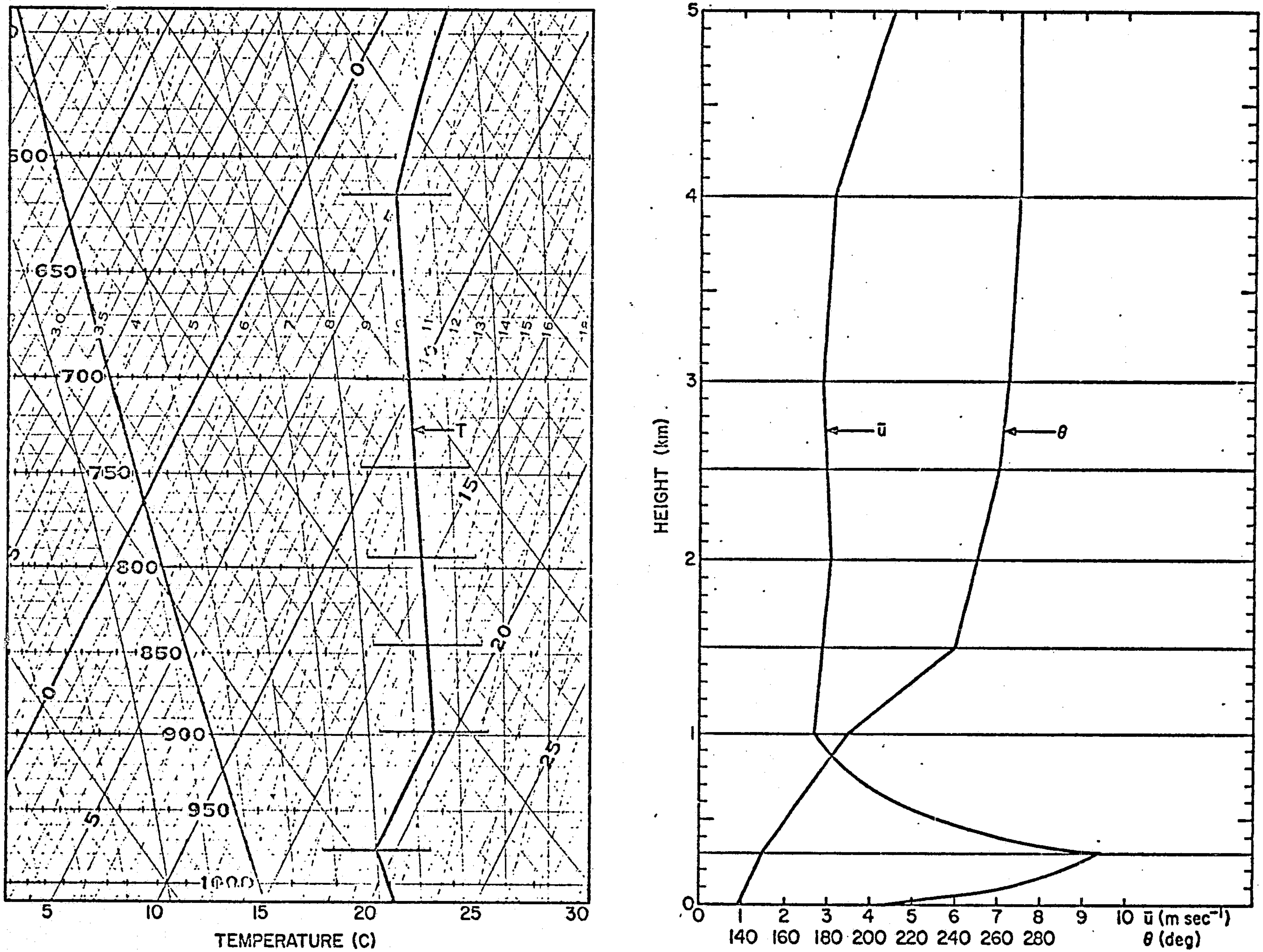

FIGURE 1-3. Vertical profiles of air temperature T, mean wind speed ū, and wind direction θ for the afternoon sea-breeze regime at KSC. Heavy horizontal lines indicate layer boundaries.

SECTION 2

CLOUD-RISE CALCULATIONS

Estimates of the maximum cloud rise were obtained from a modified form of an expression given by Briggs (1969, p. 33):

$$z_m = \left[\frac{6F}{\bar{u}\,\gamma^2\, s} + \left(\frac{r_R}{\gamma} \right)^3 \right]^{1/3} - \frac{r_R}{\gamma} \qquad (2\text{-}1)$$

where

z_m = maximum buoyant rise of cloud centroid

F = $g\, Q_H / \pi\, c_p\, \rho\, T$

g = gravitational acceleration

Q_H = rate of heat emission from burning fuel

c_p = specific heat of air

ρ = air density

T = ambient air temperature

$\bar{u}$ = mean wind speed

γ = entrainment constant

s = $\frac{g}{T} \frac{\partial \Phi}{\partial z}$

$\frac{\partial \Phi}{\partial z}$ = vertical gradient of potential temperature

r_R = reference cloud radius

The derivation of Equation (2-1) is given in Appendix A.

Table 2-1 lists values of the input parameters used in calculating the buoyant cloud rise from Equation (2-1) for both the Space Shuttle and Titan III C vehicles and for the two pad-abort situations. The vertical gradient of potential

TABLE 2-1

INPUT PARAMETERS USED TO CALCULATE BUOYANT CLOUD RISE

Parameter	Type of Pad Abort			
	Slow Burn on Pad		Single Engine Burn	
	Shuttle	Titan III C	Shuttle	Titan III C
Q_H (cal sec^{-1})	3.78×10^9	1.75×10^9	2.13×10^9	1.47×10^9
γ	0.5	0.5	0.5	0.5
r_R (m)	25	25	68.5	68.5
c_p (cal g^{-1} ^oK)	0.24	0.24	0.24	0.24
T (^oK)				
Fall	299	299	299	299
Spring	300	300	300	300
Sea Breeze	294	294	294	294
$\partial\Phi/\partial z$ (^oK m^{-1})				
Fall	0.0037	0.0033	0.0033	0.0027
Spring	0.0023	0.0024	0.0025	0.0026
Sea Breeze	0.0072	0.0081	0.0082	0.0080
$\bar{u}$ (m sec^{-1})				
Fall	6.0	6.0	6.0	6.0
Spring	7.2	7.2	7.2	7.2
Sea Breeze	4.2	4.2	4.2	4.2
ρ (g m^{-3})	1190	1190	1190	1190

temperature $\partial\Phi/\partial z$ was obtained from the temperature profiles shown in Figures 1-1, 1-2 and 1-3 by multiplying the difference between the potential temperatures at ground level and the final cloud stabilization height by the reciprocal of the final stabilization height, using an iterative calculation procedure. Values for T and $\bar{u}$ shown in Table 2-1 were also obtained from Figures 1-1, 1-2 and 1-3.

The value of Q_H for the single-engine burn on the pad was calculated from the expression

$$Q_H = \frac{W_T \cdot H}{2t'} - Q_1' - Q_2' \tag{2-2}$$

where

W_T = total weight of solid fuel in grams

H = enthalpy of solid fuel in calories per gram

t' = normal burning time of the solid-fuel engines (124 seconds for the Titan III C and 135 seconds for the Space Shuttle)

Q_1' = rate heat must be supplied to heat the gantry deluge water to boiling point = 9.20×10^7 cal sec^{-1}

Q_2' = rate heat must be supplied to vaporize deluge water = 6.82×10^8 cal sec^{-1}

The values assigned Q_1' and Q_2' are based on the assumption that 1.26×10^3 kilograms per second (Susko and Kaufman, 1971) of deluge water are used to cool the flame trench and that all the deluge water is vaporized by the rocket engine exhaust. For the case in which the solid engines burn for a 5-minute period on the pad, Q_H was calculated from the expression

$$Q_H = \frac{\left(W_T \cdot H\right)}{300 \text{ seconds}} - Q_1' - Q_2' \tag{2-3}$$

In solving Equation (2-3), the terms Q_1' and Q_2' were set equal to zero because of uncertainty as to the time duration of the full deluge water flow rate and because, even if the flow rate used for the single-engine burn calculations were to be maintained for 5 minutes, the maximum height of the stabilized cloud would decrease by less than two percent.

The value of the reference cloud radius r_R for the single-engine burn of the Titan III C was set equal to half the length of the flame trench at Launch Complex 39A at KSC (see Susko and Kaufman, 1971). The same value for r_R was used previously in a similar pad-abort calculation for a Space Shuttle vehicle prepared for Thiokol Chemical Corporation (Cramer, et al., 1972). For the slow burn on the pad caused by rupture of the solid engine casings, r_R was set equal to 25 meters under the assumption that no thrust develops and the fuel drops and burns in the immediate vicinity of the pad. The entrainment parameter γ was set equal to 0.5 in all cases. Analyses of cloud-rise data from static firings of rocket motors and normal launches have shown that this value of γ, when used in Equation (2-1), yields satisfactory estimates of cloud rise (Dumbauld, 1971; Susko and Kaufman, 1971).

The results of the cloud-rise calculations and other properties of the stabilized exhaust clouds are given in Table 2-2. Inspection of Table 2-2 shows that, as might be expected from the values of Q_H shown in Table 2-1, the final cloud stabilization heights for the Space Shuttle pad-abort cases are higher than the corresponding heights for the Titan III C pad-abort cases. The difference in final stabilization height is greatest for the pad abort in which the vehicles burn for 5 minutes on the pad, where the final height for the Space Shuttle engine burn is from 25 to 35 percent higher than the final height from the Titan III C burn. The average concentrations in the stabilized cloud shown in Table 2-2 were calculated by dividing the total amount of HCl released during each pad abort by the volume of the stabilized cloud, under the assumption that the stabilized cloud was a perfect sphere with the radius given in the table. It should be noted that ground-level concentrations, except in the direct path of the exhaust blast from single-engine burns or very close to the burning fuel components for the slow burn on the pad, must be smaller than the average concentration shown in Table 2-2 since the cloud will dilute in mixing to the ground.

TABLE 2-2

HEIGHT, RADIUS AND AVERAGE HCl CONCENTRATIONS FOR THE STABILIZED CLOUD

Meteorological Regime	Vehicle	Height (m)	Radius (m)	Average HCl Concentration (ppm)*
(a) Slow Burn On Pad				
Fall	Shuttle	1612	831	62.8
	Titan III C	1286	668	43.0
Spring	Shuttle	1770	910	48.0
	Titan III C	1341	696	38.1
Sea Breeze	Shuttle	1450	750	84.0
	Titan III C	1064	557	72.9
(b) Single Engine Burn				
Fall	Shuttle	1290	714	49.5
	Titan III C	1209	673	21.0
Spring	Shuttle	1340	739	44.8
	Titan III C	1139	638	24.8
Sea Breeze	Shuttle	1046	592	85.4
	Titan III C	917	527	43.1

*Calculated at surface temperature and pressure.

SECTION 3

CONCENTRATION MODELS

The generalized multilayer concentration models used in the calculations were taken from a complete set of computerized multilayer diffusion models developed for use in estimating toxic fuel hazards at Kennedy Space Center (Dumbauld, et al., 1970). A complete description of these models is available in the above-referenced report prepared for the Marshall Space Flight Center. The generalized models are similar in form to the conventional Gaussian plume equations described by Slade (1968, pp. 97-99) and others. However, additional terms have been added to account for the effects of mesoscale factors, such as the depth of the surface mixing layer, vertical wind shear, and precipitation scavenging. The models also contain provision for gravitational settling, decay, and variations in source dimensions, source emission time, and in meteorological structure along the downwind cloud trajectory.

In using the multilayer models, the troposphere is divided into layers in which the meteorological structure is approximately homogenous. Major layer boundaries are placed arbitrarily at the points of major discontinuities in the vertical profiles of wind, temperature, and humidity. It is assumed that there is no vertical flux of material across the major layer boundaries due to turbulent mixing; material flux across these boundaries can occur only as a result of gravitational settling or precipitation scavenging. Changes in meteorological structure at some arbitrary time or distance from the point of release can also be accommodated through use of special layer-breakdown models previously developed for this purpose in the work for Marshall Space Flight Center. As explained below, these models were used in the present study because the surface mixing layer was divided into sublayers to accommodate the height dependence of the initial vertical distribution of exhaust products.

The basic formula for the peak or maximum concentration in the K^{th} layer at some distance x downwind from the source is given by the expression

$$\chi_p = \frac{Q_K}{2\pi \sigma_{yK} \sigma_{xK}} \tag{3-1}$$

where

Q_K = source strength in units of mass per unit depth of the K^{th} layer

σ_{yK} = standard deviation of the crosswind concentration distribution in the K^{th} layer at distance x

σ_{xK} = standard deviation of the alongwind concentration distribution in the K^{th} layer at distance x

Equation (3-1) above is defined as Model 1 in the report by Dumbauld, et al. (1970), and the subset of equations defining σ_{yK} and σ_{xK} are given on pages 14 through 20 of the report. Briefly, σ_{yK} and σ_{xK} are calculated by means of simple power-law expressions relating turbulence parameters to cloud growth with distance. In this model, the source extends vertically through the entire layer; the vertical distribution of the material in the layer is assumed uniform with height and Gaussian along the crosswind (y) and alongwind (x) coordinates. The use of Equation (3-1) requires that material originating in the K^{th} layer is constrained from diffusing vertically beyond the vertical boundaries of that layer, as mentioned above.

In this study, only maximum ground-level concentrations were calculated. The surface mixing layer was divided into sublayers to accommodate the height dependence of the initial vertical distribution of HCl. The calculation of the initial distribution of HCl in the surface mixing layer is described in Section 4. Computer calculations of concentration were initiated with Model 1 given by Equation (3-1). One second after cloud stabilization, the material in the sublayers of the surface mixing layer was permitted to diffuse vertically across the sublayer boundaries.

The layer-transition model described as Model 5 by Dumbauld, et al. (1970, pp. 31-33) was used to make these calculations because it provides for the requisite vertical mixing and for identifying the contribution of the material contained in each initial sublayer to the composite ground-level concentration. The formula for the peak or maximum concentration for Model 5 is given by the expression

$$\chi_{PL} = \frac{Q_K}{4\pi\, \sigma_{yLK}\, \sigma_{xLK}}$$

$$\Bigg\{\sum_{i=0}^{\infty}\Bigg[\operatorname{erf}\left(\frac{2i\left(z_{TL}-z_{BL}\right)-z_{BK}+z_L}{\sqrt{2}\;\sigma_{zLK}}\right) + \operatorname{erf}\left(\frac{2i\left(z_{TL}-z_{BL}\right)+z_{TK}-z_L}{\sqrt{2}\;\sigma_{zLK}}\right)$$

$$+ \operatorname{erf}\left(\frac{2i\left(z_{TL}-z_{BL}\right)+2z_{BL}-z_{BK}-z_L}{\sqrt{2}\;\sigma_{zLK}}\right) + \operatorname{erf}\left(\frac{2i\left(z_{TL}-z_{BL}\right)-2z_{BL}+z_{TK}-z_L}{\sqrt{2}\;\sigma_{zLK}}\right)\Bigg] \tag{3-2}$$

$$+\sum_{i=1}^{\infty}\Bigg[\operatorname{erf}\left(\frac{-2i\left(z_{TL}-z_{BL}\right)-z_{BK}+z_L}{\sqrt{2}\;\sigma_{zLK}}\right) + \operatorname{erf}\left(\frac{-2i\left(z_{TL}-z_{BL}\right)+z_{TK}-z_L}{\sqrt{2}\;\sigma_{zLK}}\right)$$

$$+ \operatorname{erf}\left(\frac{-2i\left(z_{TL}-z_{BL}\right)+2z_{BL}-z_{BK}-z_L}{\sqrt{2}\;\sigma_{zLK}}\right) + \operatorname{erf}\left(\frac{-2i\left(z_{TL}-z_{BL}\right)-2z_{BL}+z_{TK}+z_L}{\sqrt{2}\;\sigma_{zLK}}\right)\Bigg]\Bigg\}$$

where

σ_{zLK} = standard deviation of the vertical concentration distribution in the L^{th} layer for the source originating in the K^{th} layer

σ_{yLK} = standard deviation of the crosswind concentration distribution in the L^{th} layer for the source originating in the K^{th} layer

σ_{xLK} = standard deviation of the alongwind concentration distribution in the L^{th} layer for the source originating in the K^{th} layer

z_{TL} = height of the top of the L^{th} layer

z_{BL} = height of the base of the L^{th} layer

z_{TK} = height of the top of the K^{th} layer

z_{BK} = height of the base of the K^{th} layer

z_L = height in the L^{th} layer at which the concentration is calculated

SECTION 4

VERTICAL DISTRIBUTION OF HCl IN THE SURFACE MIXING LAYER AND INITIAL CLOUD DIMENSIONS

The typical geometry of the stabilized cloud of exhaust products is illustrated in Figure 4-1, which shows the stabilized cloud dimensions calculated for the slow burn of the Space Shuttle solid engines in the spring meteorological regime. As shown in the figure, the surface mixing layer (H_m = 2000 meters) has been divided into 10 sublayers to accommodate to the vertical distribution of HCl. The height of the cloud was obtained from Equation (2-1) and the cloud-rise formula inputs given in Table 2-1. The radius of the cloud was obtained from the expression

$$r\{z\} = r_R + \gamma z \tag{4-1}$$

using the values of r_R and γ in Table 2-1. The fraction of HCl by weight in each of the K sublayers $F\{K\}$ was calculated from the relationship

$$F\{K\} = Q\left[P\{z_{TK}\} - P\{z_{BK}\}\right] \tag{4-2}$$

where

Q = total weight of HCl in the stabilized cloud

$P\{z_{TK}\}$ = integral of the Gaussian (normal) probability function between minus infinity and the top of the K^{th} layer z_{TK}

$$= P\left\{\frac{z_{TK} - z_m}{\sigma}\right\} \tag{4-3}$$

$P\{z_{BK}\}$ = integral of the Gaussian (normal) probability function between minus infinity and the base of the K^{th} layer z_{BK}

$$= P\left\{\frac{z_{BK} - z_m}{\sigma}\right\} \tag{4-4}$$

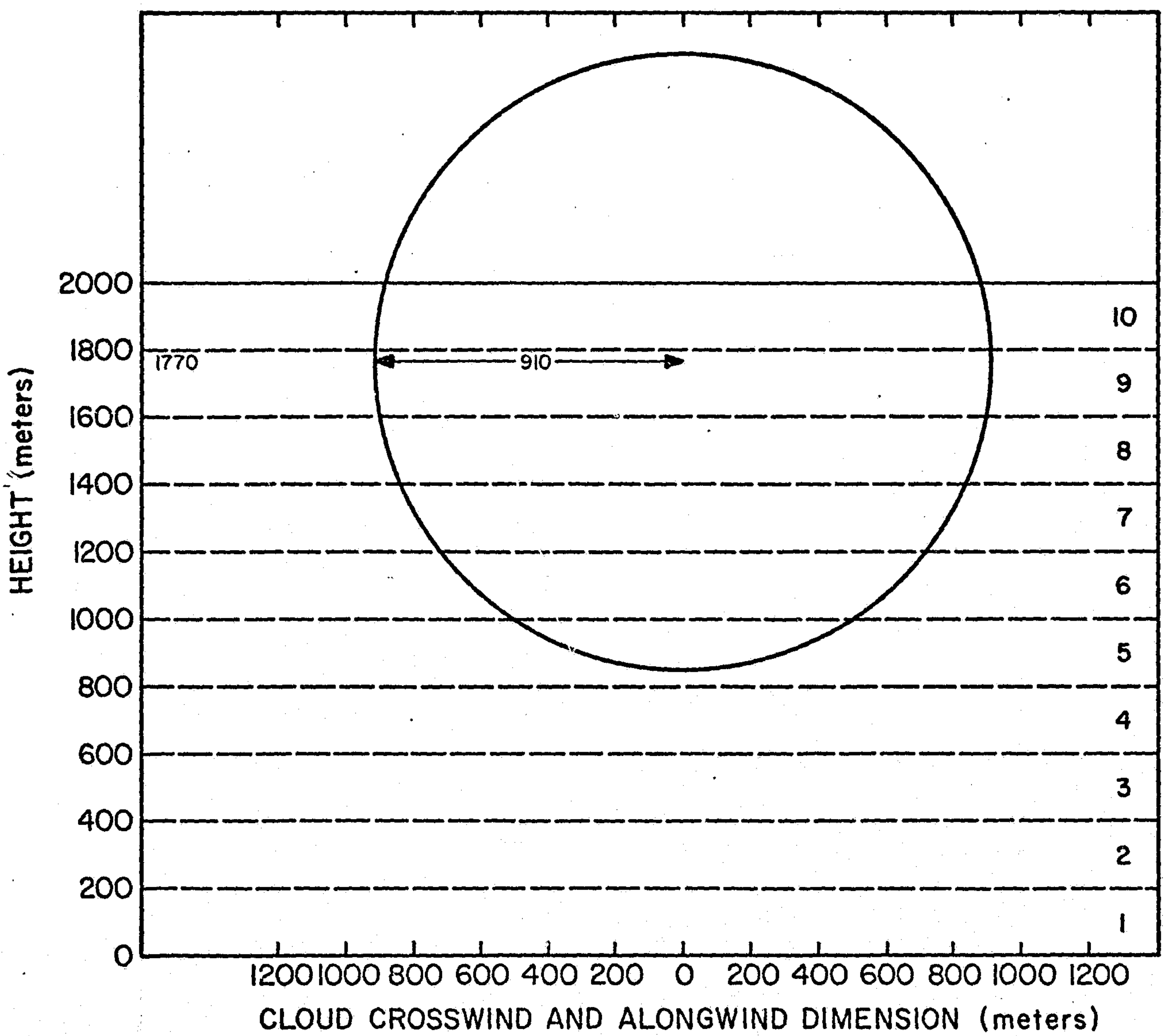

FIGURE 4-1. Geometry of the stabilized cloud for the slow burn of the Space Shuttle solid-fuel engines in the spring meteorological regime.

$$\sigma = \frac{r\{z = z_m\}}{2.15} \tag{4-5}$$

z_m = cloud stabilization height from Equation (2-1)

The models described in Section 3 above require that the source strength in each layer be specified per unit height. If Q is in units of pounds and the desired units of peak ground-level HCl concentration are parts per million, the complete expression used for the source strength input to the model calculations is

$$Q_K = \frac{F\{K\}}{(z_{TK} - z_{BK})} \left(4.536 \times 10^5 \frac{mg}{lb}\right) \left(\frac{22.4}{M}\right)\left(\frac{T}{273.16}\right) \left(\frac{1013}{P}\right) \tag{4-6}$$

where

M = molecular weight of HCl (36.47)

T = ambient temperature at the surface (^{o}K)

P = ambient surface pressure (mb)

Equations (4-2) and (4-6) were used to obtain the values of Q_K shown in the meteorological and source input tables given in Section 5 below.

The source dimensions in each of the K layers were calculated from the expressions

$$\sigma_{yo}\{K\} = \sigma_{xo}\{K\} = \begin{Bmatrix} (r_R + \gamma z')/2.15 & ; & z' \leq z_m \\ \left(r_R + \gamma(z_m - z')\right)/2.15 & ; & z' > z_m \end{Bmatrix} \tag{4-7}$$

where

z' = midpoint of the K^{th} layer

$= (z_{BK} + z_{TK})/2$

and

$$\sigma_{zo}\{K\} = \frac{z_{TK} - z_{BK}}{\sqrt{12}} \tag{4-8}$$

Equation (4-8) applies to a rectangular distribution which has been assumed for the HCl along the vertical in the K^{th} sublayer.

SECTION 5

METEOROLOGICAL AND SOURCE MODEL INPUTS

Meteorological and source model inputs used in the calculation of maximum ground-level HCl concentrations are given in Tables B-1 through B-12 in Appendix B. Tables B-1 through B-3 contain the inputs for the slow burn on the pad of the Space Shuttle solid-fuel engines for the three meteorological regimes. Tables B-4 through B-6 contain the corresponding inputs for the burn of a single Space Shuttle engine for the three regimes. The model inputs for the slow burn of the two Titan III C engines are given in Tables B-7 through B-9 and the inputs for the burn of a single Titan III C engine are given in Tables B-10 through B-12.

Requisite values of the mean wind speed, wind direction, temperature, potential temperature, and pressure were obtained from the vertical profiles shown in Figures 1-1 through 1-3. Values of the standard deviation of the wind azimuth angle at the reference height z_R of 18 meters, for a 10-minute sampling period (τ_{oK} = 600 seconds), were obtained from the expression

$$\sigma_{ABK}\{\tau_{oK} = 600 \text{ sec}; K = 1\} = \frac{R_d}{6} \tag{5-1}$$

where R_d is the wind direction range at the reference height z_R from Figure 2-11 of the report by Record, et al. (1970). The quantity σ_A was assumed to decrease with height in the mixing layer according to the expression

$$\sigma_A\{z\} = \sigma_{AR}\left(\frac{z}{z_R}\right)^{-p} \tag{5-2}$$

as suggested by Record, et al. (1970, p. 48). The power-law exponent p in Equation (5-2) is given by the expression

$$p = \log\left(\frac{\bar{u}_{TK}\{K\}}{\bar{u}_{BK}\{K\}}\right) \Big/ \log\left(\frac{z_{TK}\{K\}}{z_R}\right) \qquad (5\text{-}3)$$

Values for the standard deviation of the wind elevation angle at the reference height z_R were obtained from the expression

$$\sigma_{ER} = \sigma_{AR}\left(\frac{30}{600}\right)^{1/5} \qquad (5\text{-}4)$$

which implies that σ_{ER} is equivalent to σ_{AR} measured over a sampling period of about 30 seconds. The quantity σ_E was assumed to decrease with height in the mixing layer, similar to σ_A, according to the expression

$$\sigma_E\{z\} = \sigma_{ER}\left(\frac{z}{z_R}\right)^{-p} \qquad (5\text{-}5)$$

Values for the source strength in the various layers and the source dimensions were obtained according to the procedures outlined in Section 4 above. Values in Tables B-1 through B-12 in Appendix B for the source emission time τ_K were calculated from the expression

$$\tau_K = \begin{Bmatrix} t_B + t_z & ; & t_B + t_z \le 600 \text{ seconds} \\ 600 & ; & t_B + t_z \ge 600 \text{ seconds} \end{Bmatrix} \qquad (5\text{-}6)$$

where

t_B = propellant burning time

t_z = time to maximum cloud rise

= $\pi / s^{1/2}$ (see Equation (A-8) in Appendix A)

SECTION 6

RESULTS OF THE CALCULATIONS

6.1 DISCUSSION OF RESULTS

Figures 6-1 through 6-4 show profiles of calculated maximum ground-level concentrations resulting from pad aborts of the Space Shuttle and Titan III C vehicles in each of the three meteorological regimes described in Section 1. These concentrations were calculated by using Equations (3-1) and (3-2) in conjunction with the source and meteorological inputs in Tables B-1 through B-12 in Appendix B.

Inspection of Figure 6-1 shows that, except for the area in the immediate vicinity of the launch pad, ground-level concentrations downwind from the slow burn of the Space Shuttle solid engines are highest for the fall meteorological regime and reach a maximum of about 2.6 parts per million HCl at 7 kilometers downwind from the launch pad. In the spring meteorological regime, the highest HCl concentration outside the immediate launch area of 2 parts per million occurs at about 20 kilometers downwind from the launch pad. In the sea-breeze situation, most of the material in the stabilized cloud is above the top of the surface mixing layer which is at 300 meters. Thus, beyond about 4 kilometers from the launch pad, maximum ground-level HCl concentrations are lowest for the sea-breeze situation.

Figure 6-2 shows the maximum HCl concentrations downwind from a 135-second burn of a single Space Shuttle engine with the vehicle restrained on the launch pad. Highest HCl concentrations downwind from the launch area again occur during the fall meteorological regime, when the maximum ground-level concentration is about 4.3 parts per million at 7 kilometers from the pad. Maximum HCl concentrations of 2.2 parts per million occur at distances of 12 to 13 kilometers downwind from the pad for the spring meteorological regime. Maximum HCl concentrations are again lowest for the sea-breeze regime. Comparison of Figures 6-1 and 6-2 shows that concentrations downwind from the launch pad are higher for the 135-second burn of a single engine than for both engines burning on the pad over a

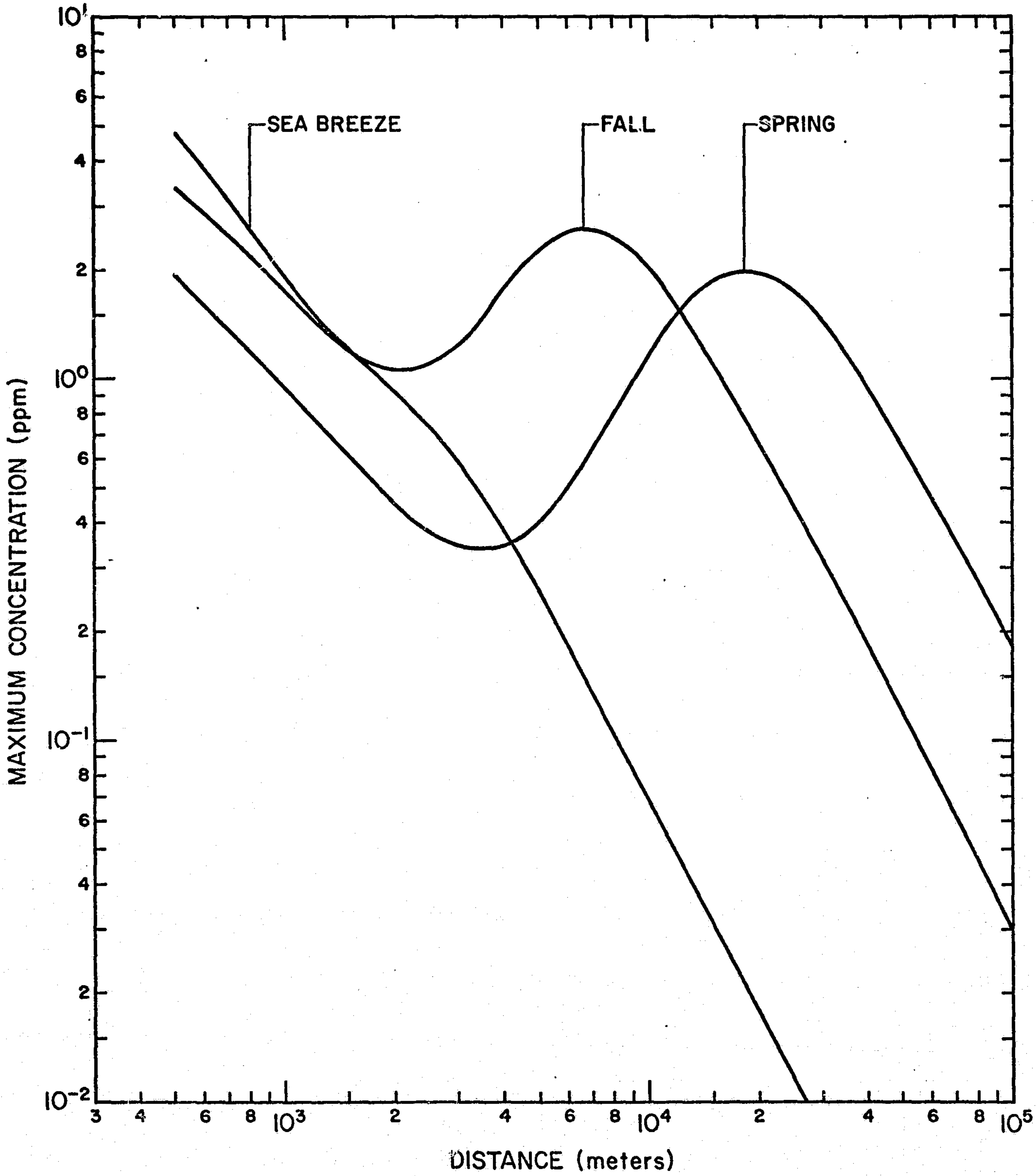

FIGURE 6-1. Maximum ground-level HCl concentrations downwind from a slow burn on the pad of the two solid engines of the Space Shuttle vehicle.

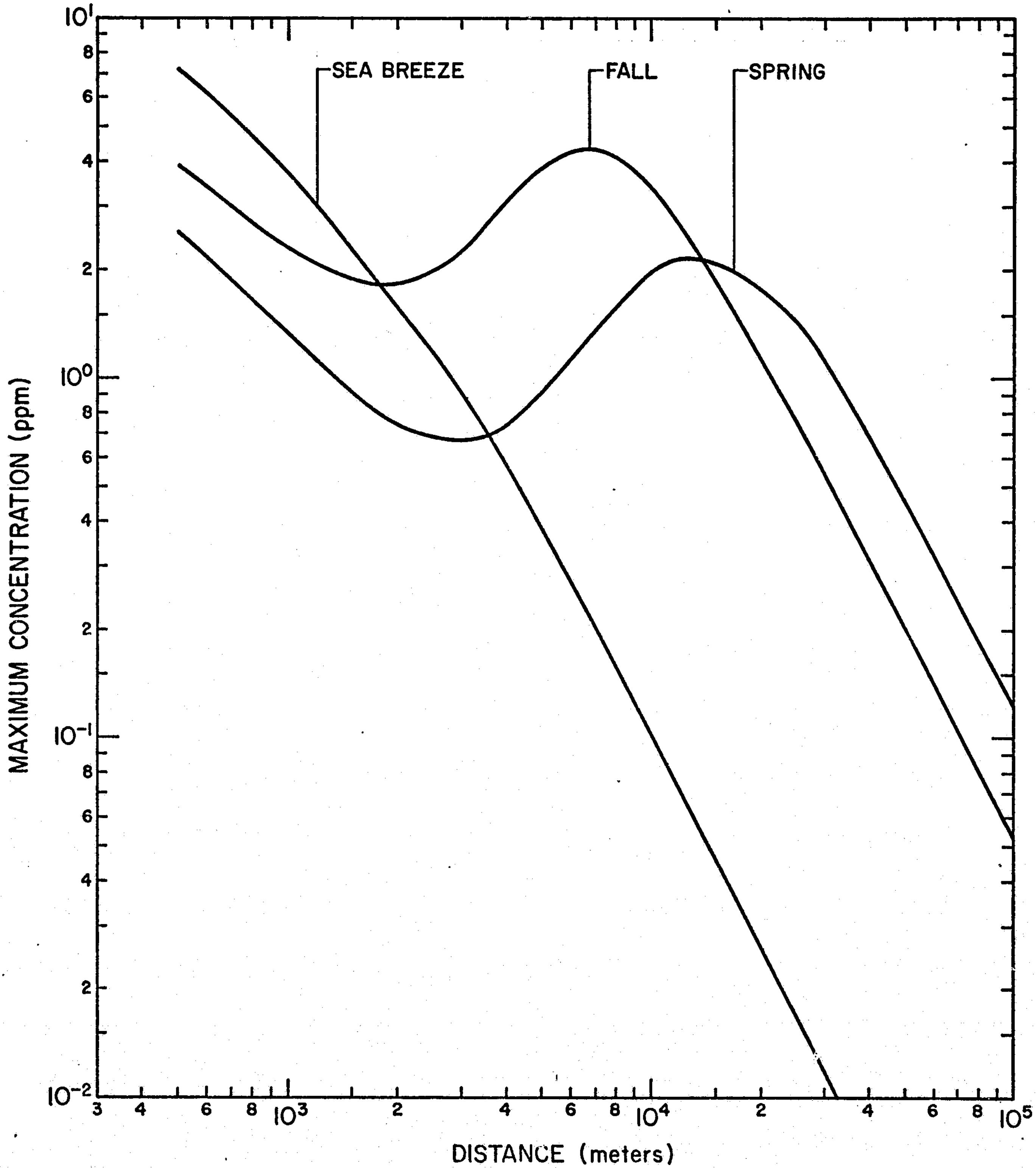

FIGURE 6-2. Maximum ground-level HCl concentrations downwind from a 135-second on-pad burn of one solid engine of the Space Shuttle vehicle.

5-minute period. This occurs primarily because the larger cloud stabilization height in the slow burn case more than compensates for the increased amount of HCl available when both engines burn.

Maximum HCl concentrations downwind from a slow burn on the pad of a Titan III C vehicle and from a 124-second burn of a single engine with the vehicle restrained on the pad are respectively shown in Figures 6-3 and 6-4. In both pad-abort cases for the Titan III C vehicle, the concentration profiles resemble those for the Space Shuttle pad-abort cases with concentrations downwind from the launch area being highest for the fall meteorological regime and lowest for the sea-breeze regime. However, for the fall and spring meteorological regimes, the maximum concentrations are higher for the two-engine burn over a 5-minute period rather than for the single-engine burn. For the Titan III C vehicle, the difference in the heights of the stabilized cloud for the two different types of abort cases is not sufficient to overcome the effect at ground level of the greater amount of HCl released when both engines burn over the 5-minute period. Ground-level HCl concentrations downwind from the launch pad during the sea-breeze regime are greater for the single-engine burn than for the slow burn of both engines over a 5-minute period. In any case, maximum HCl concentrations outside the immediate launch area do not exceed a 2.8 parts per million for any meteorological regime or pad-abort situation considered.

Comparison of the maximum ground-level HCl concentration profiles shown in Figures 6-1 and 6-3 for the slow burn on the pad shows that downwind concentrations beyond several kilometers from the pad are similar for both the Titan III C and Space Shuttle vehicles during the fall and sea-breeze meteorological regimes. In the spring meteorological regime, maximum ground-level HCl concentrations are greater at distances beyond 10 kilometers from the pad for the burn of the Space Shuttle engines. Comparison of the profiles in Figures 6-2 and 6-4 for the single-engine burns shows that the concentrations are greater downwind from

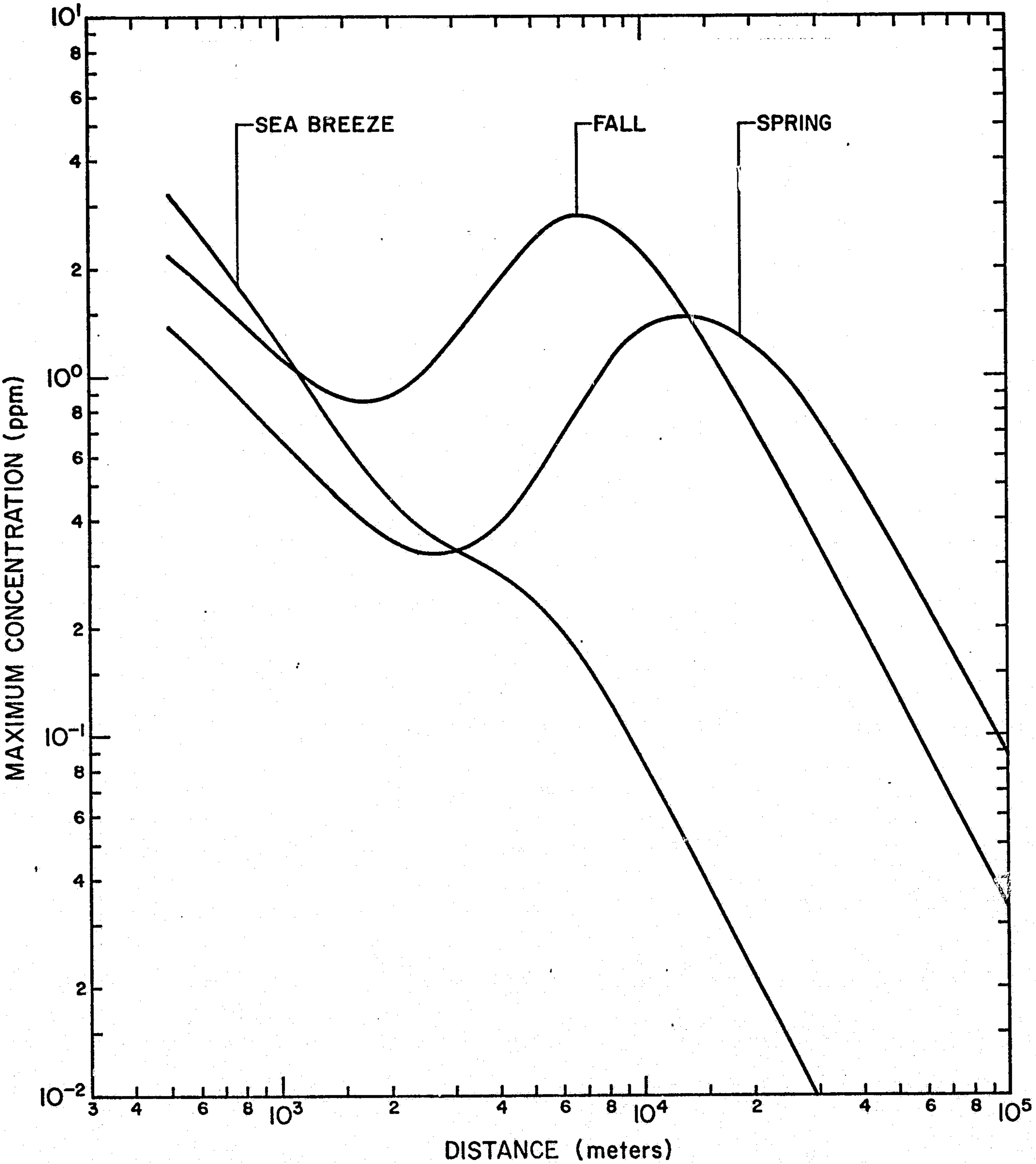

FIGURE 6-3. Maximum ground-level HCl concentrations downwind from a slow burn on pad of the two solid engines of the Titan III C vehicle.

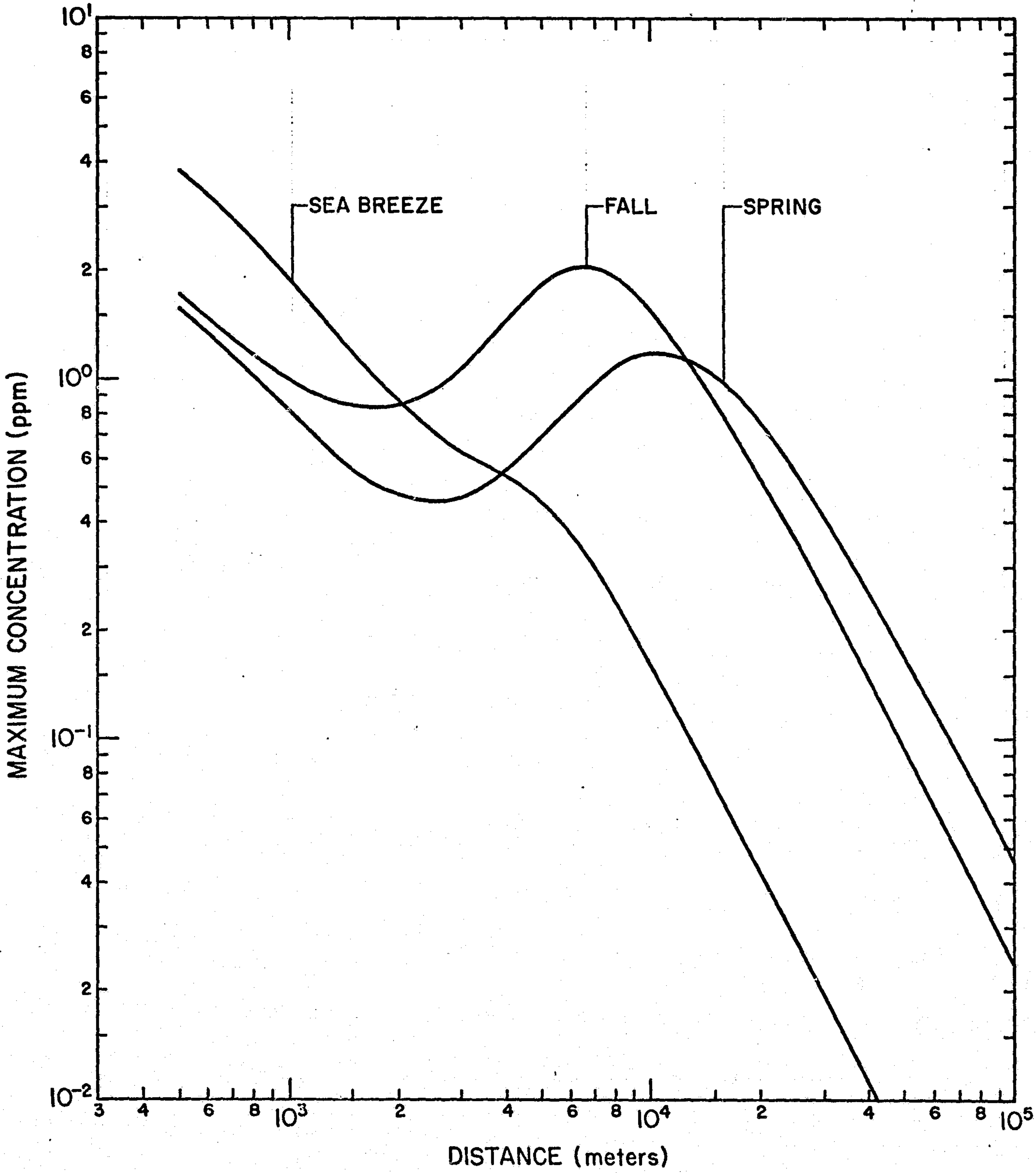

FIGURE 6-4. Maximum ground-level HCl concentrations downwind from a 124-second on-pad burn of one solid engine of the Titan III C vehicle.

the Space Shuttle pad abort than from the Titan III C abort for the fall and spring meteorological regimes. Ground-level HCl concentrations for both vehicles are approximately equal during the sea-breeze regime.

6.2 COMPARISON OF RESULTS WITH PREVIOUS PAD-ABORT HAZARD CALCULATIONS

Similar calculations of maximum ground-level HCl concentrations for a single engine on-pad burn of the Space Shuttle vehicle at Kennedy Space Center are contained in a report previously prepared for Thiokol Chemical Corporation (Cramer, et al., 1972, pp. 38-39). Table 6-1 lists the maximum HCl ground-level concentrations, at distances greater than 1 kilometer from the launch area, from Figure 6-2 above and from Figure 4-4 in the Thiokol report. The two sets of maximum concentration estimates are in close agreement and the differences are well within the probable confidence limits of such calculations. The small differences between the two sets are explained by differences in the methods used to calculate buoyant plume rise, differences in the number of sublayers into which the surface layer was divided, and small differences in the total weight of fuel assumed to be contained in a single solid-propellant engine. ["identical meteorological and space shuttle vehicle inputs" ???]

Calculations of the maximum ground-level HCl concentrations resulting from a slow burn on the pad of the two zero stage engines of a Titan III D vehicle were previously made by Cramer, et al. (1970) in a hazard study prepared for Vandenberg Air Force Base. The zero stage engines for the Titan III D are the same as for the Titan III C vehicle considered in this report. Close to the launch pad, the calculated HCl ground-level concentrations resulting from the slow burn of the Titan III D vehicle at Vandenberg Air Force Base (see Cramer, et al., 1970, Figure 6-1, p. 96) are approximately ten times larger than the concentration estimates for the Titan III C at Kennedy Space Center shown in Figure 6-3. At downwind distances of 10 to 20 kilometers, the two sets of estimates differ by less than a factor

TABLE 6-1

COMPARISON OF CALCULATED MAXIMUM HCl GROUND-LEVEL CONCENTRATIONS FOR A SINGLE ENGINE BURN ON THE PAD OF THE SPACE SHUTTLE VEHICLE AT KENNEDY SPACE CENTER

Meteorological Regime	HCl Concentrations (ppm)	
	From Figure 6-2	From Figure 4-4 in Cramer, et al. (1970)
Fall	4.3	4.8
Spring	2.2	2.8
Sea-Breeze	3.7	3.5

of two. The above differences are principally explained by differences in the assumptions as to the total weight of HCl contained in the surface mixing layer and the form of the vertical distribution of this material. In the Titan III D calculations, the total weight of HCl in the surface layer is 2.5 times larger than that assumed for the Titan III C sea-breeze regime case at Kennedy Space Center. The depth of the surface mixing layer is approximately the same in both cases. Also, in the Titan III D calculations, the HCl was assumed to be uniformly distributed with height in the surface mixing layer above the pad. In the Titan III C calculations for Kennedy Space Center, the vertical distribution of HCl in the surface layer was assumed to be Gaussian with the bulk of the HCl contained at the top of the layer. In retrospect, we feel that the assumptions made in the Titan III D pad-abort calculations concerning the amount of HCl contained in the surface layer and the form of the vertical distribution of HCl were unrealistic and led to large overestimates of the ground-level HCl concentrations in the first 10 kilometers downwind from the launch pad at Vandenberg Air Force Base.

Wow!!

I wonder what would be realistic for shuttle at Vandenberg?

APPENDIX A

DERIVATION OF MAXIMUM PLUME RISE FORMULA

The following derivation of Equation (2-1) for the maximum buoyant rise of the hot plume of combustion products from the on-pad burning of solid propellant is based principally on material contained in a preprint of a paper by G. A. Briggs (1970) presented at the Second International Clean Air Congress.

The derivation begins under the assumptions that we are dealing with a plume in which the axis is only slightly inclined above the horizontal, the density ρ is nearly the same as the density of the ambient air, and the horizontal component of motion is approximately equal to the mean wind speed $\bar{u}$. In the case of a buoyant plume, the buoyancy flux divided by $\pi \rho$ is given by the time derivative of the vertical momentum flux divided by $\pi \rho$

$$\frac{d}{dt}\left(w\,\bar{u}\,r^2\right) = \bar{u}\,\frac{d(w\,\bar{u}\,r^2)}{dx} = b\,\bar{u}\,r^2 \tag{A-1}$$

where

w = vertical velocity component

r = plume radius

x = $\bar{u}\,t$

b = characteristic buoyant acceleration of the plume

The decay of the buoyancy flux with time, assuming an adiabatic process, is expressed by

$$\frac{d}{dt}\left(b\,\bar{u}\,r^2\right) = \bar{u}\,\frac{d(b\,\bar{u}\,r^2)}{dx} = -\,w\,s\,\bar{u}\,r^2 \tag{A-2}$$

where

$$s = \frac{g}{T}\,\frac{\partial \Phi}{\partial z}$$

g = gravitational acceleration

T = ambient air temperature

$\frac{\partial \Phi}{\partial z}$ = vertical gradient of ambient potential temperature

Differentiating Equation (A-1) with respect to time, assuming $x = \bar{u}\,t$, and substituting from Equation (A-2) leads to the expression

$$\bar{u}^2 \frac{d^2 (w\,\bar{u}\,r^2)}{dx^2} = -\,s\,(w\,\bar{u}\,r^2) \qquad \text{(A-3)}$$

If the quantity s is positive and approximately constant with height, Equation (A-3) indicates that the vertical momentum flux can be expressed by the harmonic function

$$\left(w\,\bar{u}\,r^2\right) = F_m \cos\left(s^{1/2}\,\frac{x}{\bar{u}}\right) + \frac{F}{s^{1/2}} \sin\left(s^{1/2}\,\frac{x}{\bar{u}}\right) \qquad \text{(A-4)}$$

where

$$F_m = \left(w\,\bar{u}\,r^2\right)_{t=0} = w_o^2\,r_o^2$$

$$F = \left(b\,\bar{u}\,r^2\right)_{t=0} = b\,w_o\,r_o^2$$

The above derivation is based on conservation assumptions and is independent of the behavior of r. Briggs (1970) notes that a simple linear relationship for r accounts very well for the great bulk of observed plume rises, even including plumes that are more nearly vertical than horizontal. This relationship can be expressed by $r = \gamma z$, where z is the rise of the plume centerline above the source and γ is an entrainment constant. In this report, we have used a modified equation for r to account for the large initial dimensions in the case of the on-pad abcrt of the Titan III C and Space Shuttle vehicles. The modified equation has the form

$$r = r_R + \gamma z \tag{A-5}$$

where r_R is the reference cloud radius at the source.

Substitution of Equation (A-5) into Equation (A-4) and the use of $w = \bar{u}\frac{dz}{dx}$ yields

$$\bar{u}^2 \left(r_R + \gamma z\right)^2 dz = F_m \cos\left(s^{1/2} \frac{x}{\bar{u}}\right)dx + \frac{F}{s^{1/2}} \sin\left(s^{1/2} \frac{x}{\bar{u}}\right)dx \tag{A-6}$$

Integrating Equation (A-6) and solving for z with the boundary condition that $z = 0$ when $x = t = 0$ gives

$$z = \left[\frac{3\,F_m}{\gamma^2\,\bar{u}\,s^{1/2}} \sin\left(s^{1/2}\,t\right) + \frac{3F}{\bar{u}\,\gamma^2\,s}\left(1 - \cos\left(s^{1/2}\,t\right)\right) + \left(\frac{r_R}{\gamma}\right)^3\right]^{1/3} - \frac{r_R}{\gamma} \tag{A-7}$$

In the case of an on-pad burn of a solid rocket motor, the buoyancy term is dominant. Thus, the buoyant rise of the plume is given by

$$z(t) = \left[\frac{3F}{\bar{u}\,\gamma^2\,s}\left(1 - \cos\left(s^{1/2}\,t\right)\right) + \left(\frac{r_R}{\gamma}\right)^3\right]^{1/3} - \frac{r_R}{\gamma} \tag{A-8}$$

The maximum buoyant rise z_m of the plume is expressed by

$$z_m = \left[\frac{6F}{\bar{u}\,\gamma^2\,s} + \left(\frac{r_R}{\gamma}\right)^3\right]^{1/3} - \frac{r_R}{\gamma} \tag{A-9}$$

which is identical to Equation (2-1) in the body of the report.

The initial buoyancy flux parameter F may be calculated by assuming that the molecular weights and specific heats of the ambient air and the plume are approximately equal. Thus,

$$F = b\, w_o\, r_o^2 = g\left(1 - \rho_s/\rho\right)\, w_o\, r_o^2 \tag{A-10}$$

where

g = gravitational acceleration

ρ = ambient air density

ρ_s = plume density

Substitution from the Ideal Gas Law gives

$$F = g\, \frac{\Delta T}{T_s}\, w_o\, r_o^2 \tag{A-11}$$

where

$\Delta T = T_s - T$

T = ambient air temperature

T_s = plume temperature

Use of the Second Law of Thermodynamics yields the form of F shown in Section 2 of the report

$$F = \frac{g\, Q_H}{\pi\, \rho\, c_p\, T} \tag{A-12}$$

where

c_p = specific heat of air

Q_H = rate of heat emission from the burning fuel

APPENDIX B

TABLES OF METEOROLOGICAL AND SOURCE INPUTS

This appendix contains tables of source and meteorological inputs used in the calculation of maximum HCl concentrations downwind from pad aborts of the Space Shuttle and Titan III C vehicles. Tables B-1 through B-3 contain the inputs for the slow burn on the pad of the Space Shuttle solid-fuel engines for three meteorological regimes. Tables B-4 through B-6 contain corresponding inputs for the burn of a single Space Shuttle engine. The model inputs for the slow burn of two Titan III C engines are given in Tables B-7 through B-9, and the inputs for the burn of a single Titan III C engine are given in Tables B-10 through B-12.

TABLE B-1

METEOROLOGICAL AND SOURCE INPUTS FOR A SLOW BURN ON THE PAD OF A SPACE SHUTTLE VEHICLE - FALL METEOROLOGICAL REGIME

Parameter	Units	Layer						
		1	2	3	4	5	6	7
Q_K	ppm m^{-1}	9.77×10^4	5.49×10^5	2.69×10^6	1.01×10^6	2.25×10^7	3.61×10^7	
z_R	m	18						
$\bar{u}_R$	m sec^{-1}	4.7						
$\sigma_{AR}\{\tau_{oK}\}$	deg	12.0						
σ_{ER}	deg	6.6						
τ_{oK}	sec	600	600	600	600	600	600	
τ_K	sec	586	586	586	586	586	586	
$\sigma_{ATK}\{\tau_{oK}\}$	deg	9.41	8.78	8.42	8.18	8.08	8.00	
$\sigma_{ABK}\{\tau_{oK}\}$	deg	14.98	9.41	8.78	8.42	8.18	8.08	
$\sigma_{yo}\{K\}$	m	34.9	81.4	127.9	174.4	209.3	232.6	
α_K		1	1	1	1	1	1	
σ_{ETK}	deg	5.18	4.83	4.63	4.50	4.45	4.40	
σ_{EBK}	deg	8.24	5.18	4.83	4.63	4.50	4.45	
$\sigma_{zo}\{K\}$	m	57.7	57.7	57.7	57.7	28.9	28.9	
$\sigma_{xo}\{K\}$	m	34.9	81.4	127.9	174.4	209.3	232.6	

TABLE B-1 (Continued)

Parameter	Units	Layer						
		1	2	3	4	5	6	7
β_K		1	1	1	1	1	1	
z_{TK}	m	200	400	600	800	900	1000	
z_{BK}	m	2	200	400	600	800	900	
$\bar{u}_{TK}$	m sec^{-1}	5.97	6.39	6.65	6.85	6.93	7.00	
$\bar{u}_{BK}$	m sec^{-1}	3.78	5.97	6.39	6.65	6.85	6.93	
θ_{TK}	deg	95.8	101.6	107.4	113.2	116.1	119.0	
θ_{BK}	deg	90.0	95.8	101.6	107.4	113.2	116.1	
Φ_{TK}	^oK	298.6	299.1	299.3	299.8	299.9	299.9	
Φ_{BK}	^oK	297.9	298.6	299.1	299.3	299.8	299.9	
T_{TK}	^oK	297.7	296.2	294.2	292.7	291.7	290.7	
T_{BK}	^oK	299.0	297.7	296.2	294.2	292.7	291.7	
P_{TK}	mb	990	967	944	920	908	898	
P_{BK}	mb	1013	990	967	944	920	908	
t*	sec	1	1	1	1	1	1	
Model No.		5	5	5	5	5	5	

TABLE B-2

METEOROLOGICAL AND SOURCE INPUTS FOR A SLOW BURN ON THE PAD OF A SPACE SHUTTLE VEHICLE - SPRING METEOROLOGICAL REGIME

Parameter	Units	Layer									
		1	2	3	4	5	6	7	8	9	10
Q_K	ppm m^{-1}	7.88×10^4	3.79×10^5	1.70×10^6	6.14×10^6	1.78×10^7	4.14×10^7	7.72×10^7	1.16×10^8	1.40×10^8	1.35×10^8
z_R	m	18									
$\bar{u}_R$	m sec^{-1}	6									
$\sigma_{AR}\{\tau_{oK}\}$	deg	7									
σ_{ER}	deg	3.8									
τ_{oK}	sec	600	600	600}	600	600	600	600	600	600	600
τ_K	sec	600	600	600	600	600	600	600	600	600	600
$\sigma_{ATK}\{\tau_{oK}\}$	deg	6.25	6.04	5.93	5.85	5.79	5.74	5.70	5.66	5.63	5.60
$\sigma_{ABK}\{\tau_{oK}\}$	deg	7.00	6.25	6.04	5.93	5.85	5.79	5.74	5.70	5.66	5.63
$\sigma_{yo}\{K\}$	m	34.9	81.4	127.9	174.4	220.9	267.4	314.0	360.5	407.0	393.0
α_K		1	1	1	1	1	1	1	1	1	1
σ_{ETK}	deg	3.39	3.28	3.22	3.17	3.14	3.11	3.09	3.07	3.06	3.04
σ_{EBK}	deg	4.14	3.39	3.28	3.22	3.17	3.14	3.11	3.09	3.07	3.06
$\sigma_{zo}\{K\}$	m	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7
$\sigma_{xo}\{K\}$	m	34.9	81.4	127.9	174.4	220.9	267.4	314.0	360.5	407.0	393.0

TABLE B-2 (Continued)

Parameter	Units	Layer									
		1	2	3	4	5	6	7	8	9	10
β_K		1	1	1	1	1	1	1	1	1	1
z_{TK}	m	200	400	600	800	1000	1200	1400	1600	1800	2000
z_{BK}	m	2	200	400	600	800	1000	1200	1400	1600	1800
$\bar{u}_{TK}$	m sec^{-1}	6.72	6.95	7.08	7.18	7.26	7.32	7.37	7.42	7.46	7.50
$\bar{u}_{BK}$	m sec^{-1}	5.41	6.72	6.72	7.08	7.18	7.26	7.32	7.37	7.42	7.46
θ_{TK}	deg	108	116	124	132	140	148	156	164	172	180
θ_{BK}	deg	100	108	116	124	132	140	148	156	164	172
Φ_{TK}	^oK	299.6	299.9	300.4	301.1	301.6	302.0	302.5	302.9	302.9	303.5
Φ_{BK}	^oK	298.9	299.6	299.9	300.4	301.1	301.6	302.0	302.5	302.9	303.5
T_{TK}	^oK	298.7	297.0	295.5	294.0	292.5	290.7	289.2	287.5	285.7	284.2
T_{BK}	^oK	300.0	298.7	297.0	295.5	294.0	292.5	290.7	289.2	287.5	285.7
P_{TK}	mb	990	967	944	920	898	875	855	835	815	795
P_{BK}	mb	1013	990	967	944	920	898	875	855	835	815
t*	sec	1	1	1	1	1	1	1	1	1	1
Model No.		5	5	5	5	5	5	5	5	5	5

TABLE B-3

METEOROLOGICAL AND SOURCE INPUTS FOR A SLOW BURN ON THE PAD OF A SPACE SHUTTLE VEHICLE - SEA-BREEZE METEOROLOGICAL REGIME

Parameter	Units	Layer						
		1	2	3	4	5	6	7
Q_K	ppm m^{-1}	8.02×10^4	1.71×10^5	4.75×10^5				
z_R	m	18						
$\bar{u}_R$	m sec^{-1}	4.5						
$\sigma_{AR}\{\tau_{oK}\}$	deg	12						
σ_{ER}	deg	6.6						
τ_{oK}	sec	600	600	600				
τ_K	sec	503	503	503				
$\sigma_{ATK}\{\tau_{oK}\}$	deg	7.62	6.35	5.70				
$\sigma_{ABK}\{\tau_{oK}\}$	deg	21.5	7.62	6.35				
$\sigma_{yo}\{K\}$	m	23.3	46.5	69.8				
α_K		1	1	1				
σ_{ETK}	deg	4.18	3.48	3.12				
σ_{EBK}	deg	11.84	4.18	3.48				
$\sigma_{zo}\{K\}$	m	28.9	28.9	28.9				
$\sigma_{xo}\{K\}$	m	23.3	46.5	69.8				

TABLE B-3 (Continued)

Parameter	Units	Layer						
		1	2	3	4	5	6	7
β_K		1	1	1				
z_{TK}	m	100	200	300				
z_{BK}	m	2	100	200				
$\bar{u}_{TK}$	m sec^{-1}	7.09	8.53	9.50				
$\bar{u}_{BK}$	m sec^{-1}	2.51	7.09	8.53				
θ_{TK}	deg	143.3	146.7	150.0				
θ_{BK}	deg	140.0	143.3	146.7				
Φ_{TK}	^oK	293.7	294.0	294.2				
Φ_{BK}	^oK	292.9	293.7	294.0				
T_{TK}	^oK	293.7	293.2	292.2				
T_{BK}	^oK	294.0	293.7	293.2				
P_{TK}	mb	1000	990	977				
P_{BK}	mb	1013	1000	990				
t*	sec	1	1	1				
Model No.		5	5	5				

TABLE B-4

METEOROLOGICAL AND SOURCE INPUTS FOR A SINGLE ENGINE BURN ON THE PAD FOR THE SPACE SHUTTLE - FALL METEOROLOGICAL REGIME

Parameter	Units	Layer						
		1	2	3	4	5	6	7
Q_K	ppm m^{-1}	1.93×10^5	1.19×10^6	5.71×10^6	1.43×10^7	2.43×10^7	3.78×10^7	5.37×10^7
z_R	m	18						
$\bar{u}_R$	m sec^{-1}	4.7						
$\sigma_{AR}\{\tau_{oK}\}$	deg	12.0						
σ_{ER}	deg	6.6						
τ_{oK}	sec	600	600	600	600	600	600	600
τ_K	sec	438	438	438	438	438	438	438
$\sigma_{ATK}\{\tau_{oK}\}$	deg	9.41	8.78	8.42	8.29	8.18	8.08	8.00
$\sigma_{ABK}\{\tau_{oK}\}$	deg	14.98	9.41	8.78	8.42	8.29	8.18	8.08
$\sigma_{yo}\{K\}$	m	55.1	101.6	148.1	183.0	206.3	229.5	252.8
α_K		1	1	1	1	1	1	1
σ_{ETK}	deg	5.18	4.83	4.63	4.56	4.50	4.45	4.40
σ_{EBK}	deg	8.24	5.18	4.83	4.63	4.56	4.50	4.45
$\sigma_{zo}\{K\}$	m	57.7	57.7	57.7	28.87	28.87	28.87	28.87
$\sigma_{xo}\{K\}$	m	55.1	101.6	148.1	183.0	206.3	229.5	252.8

TABLE B-4 (Continued)

Parameter	Units	Layer						
		1	2	3	4	5	6	7
β_K		1	1	1	1	1	1	1
z_{TK}	m	200	400	600	700	800	900	1000
z_{BK}	m	2	200	400	600	700	800	900
$\bar{u}_{TK}$	m sec^{-1}	5.97	6.39	6.65	6.76	6.85	6.93	7.00
$\bar{u}_{BK}$	m sec^{-1}	3.78	5.97	6.39	6.65	6.76	6.85	6.93
θ_{TK}	deg	95.8	101.6	107.4	110.3	113.2	116.1	119.0
θ_{BK}	deg	90.0	95.8	101.6	107.4	110.3	113.2	116.1
Φ_{TK}	^oK	298.6	299.1	299.3	299.5	299.8	299.9	299.9
Φ_{BK}	^oK	297.9	298.6	299.1	299.3	299.5	299.8	299.9
T_{TK}	^oK	297.7	296.2	294.2	293.4	292.7	291.7	290.7
T_{BK}	^oK	299.0	297.7	296.2	294.2	293.4	292.7	291.7
P_{TK}	mb	990	967	944	930	920	908	898
P_{BK}	mb	1013	990	967	944	930	920	908
t*	sec	1	1	1	1	1	1	1
Model No.		5	5	5	5	5	5	5

TABLE B-5

METEOROLOGICAL AND SOURCE INPUTS FOR A SINGLE ENGINE ON-PAD BURN OF THE SPACE SHUTTLE VEHICLE - SPRING METEOROLOGICAL REGIME

Parameter	Units	Layer									
		1	2	3	4	5	6	7	8	9	10
Q_K	ppm m^{-1}	1.71×10^5	1.00×10^6	4.73×10^6	1.60×10^7	3.91×10^7	6.84×10^7	8.62×10^7	7.81×10^7	5.09×10^7	2.38×10^7
z_R	m	18									
$\bar{u}_R$	m sec^{-1}	6									
$\sigma_{AR}\{\tau_{oK}\}$	deg	7									
σ_{ER}	deg	3.8									
τ_{oK}	sec	600	600	600	600	600	600	600	600	600	600
τ_K	sec	486	486	486	486	486	486	486	486	486	486
$\sigma_{ATK}\{\tau_{oK}\}$	deg	6.25	6.04	5.93	5.85	5.79	5.74	5.70	5.66	5.63	5.60
$\sigma_{ABK}\{\tau_{oK}\}$	deg	7.77	6.25	6.04	5.93	5.85	5.79	5.74	5.70	5.66	5.63
$\sigma_{yo}\{K\}$	m	55.1	101.6	148.1	194.7	241.2	287.7	334.2	306.3	259.8	213.3
α_K		1	1	1	1	1	1	1	1	1	1
σ_{ETK}	deg	3.39	3.28	3.22	3.17	3.14	3.11	3.09	3.07	3.06	3.04
σ_{EBK}	deg	4.14	3.39	3.28	3.22	3.17	3.14	3.11	3.09	3.07	3.06
$\sigma_{zo}\{K\}$	m	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7
$\sigma_{xo}\{K\}$	m	55.1	101.6	148.1	194.7	241.2	287.7	334.2	306.3	259.8	213.3

TABLE B-5 (Continued)

Parameter	Units	Layer									
		1	2	3	4	5	6	7	8	9	10
β_K		1	1	1	1	1	1	1	1	1	1
z_{TK}	m	200	400	600	800	1000	1200	1400	1600	1800	2000
z_{BK}	m	2	200	400	600	800	1000	1200	1400	1600	1800
$\bar{u}_{TK}$	m sec^{-1}	6.72	6.95	7.08	7.18	7.26	7.32	7.37	7.42	7.46	7.50
$\bar{u}_{BK}$	m sec^{-1}	5.41	6.72	6.95	7.08	7.18	7.26	7.32	7.37	7.42	7.46
θ_{TK}	deg	108	116	124	132	140	148	156	164	172	180
θ_{BK}	deg	100	108	116	124	132	140	148	156	164	172
Φ_{TK}	^oK	299.6	299.9	300.4	301.1	301.6	302.0	302.5	302.9	302.9	303.5
Φ_{BK}	^oK	298.9	299.6	299.9	300.4	301.1	301.6	302.0	302.5	302.9	303.5
T_{TK}	^oK	298.7	297.0	295.5	294.0	292.5	290.7	289.2	287.5	285.7	284.2
T_{BK}	^oK	300.0	298.7	297.0	295.5	294.0	292.5	290.7	289.2	287.5	285.7
P_{TK}	mb	990	967	944	920	898	875	855	835	815	795
P_{BK}	mb	1013	990	967	944	920	898	875	855	835	815
t*	sec	1	1	1	1	1	1	1	1	1	1
Model No.		5	5	5	5	5	5	5	5	5	5

TABLE B-6

METEOROLOGICAL AND SOURCE INPUTS FOR A SINGLE-ENGINE ON-PAD BURN OF THE SPACE SHUTTLE VEHICLE - SEA-BREEZE METEOROLOGICAL REGIME

Parameter	Units	Layer						
		1	2	3	4	5	6	7
Q_K	ppm m^{-1}	2.17×10^5	5.64×10^5	1.70×10^5				
z_R	m	18						
$\bar{u}_R$	m sec^{-1}	4.5						
$\sigma_{AR}\{\tau_{oK}\}$	deg	12						
σ_{ER}	deg	6.6						
τ_{oK}	sec	600	600	600				
τ_K	sec	325	325	325				
$\sigma_{ATK}\{\tau_{oK}\}$	deg	7.62	6.35	5.70				
$\sigma_{ABK}\{\tau_{oK}\}$	deg	21.5	7.62	6.35				
$\sigma_{yo}\{K\}$	m	43.5	66.7	90.0				
α_K		1	1	1				
σ_{ETK}	deg	4.18	3.48	3.12				
σ_{EBK}	deg	11.84	4.18	3.48				
$\sigma_{zo}\{K\}$	m	28.87	28.87	28.87				
$\sigma_{xo}\{K\}$	m	43.5	66.7	90.0				

TABLE B-6 (Continued)

Parameter	Units	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
β_K		1	1	1				
z_{TK}	m	100	200	300				
z_{BK}	m	2	100	200				
$\bar{u}_{TK}$	m sec^{-1}	7.09	8.53	9.5				
$\bar{u}_{BK}$	m sec^{-1}	2.51	7.09	8.53				
θ_{TK}	deg	143.3	146.7	150				
θ_{BK}	deg	140	143.3	146.7				
Φ_{TK}	^{o}K	293.7	294.0	294.2				
Φ_{BK}	^{o}K	292.9	293.7	294.0				
T_{TK}	^{o}K	293.7	293.2	292.2				
T_{BK}	^{o}K	294.0	293.7	293.2				
P_{TK}	mb	1000	990	977				
P_{BK}	mb	1013	1000	990				
t*	sec	1	1	1				
Model No.		5	5	5				

TABLE B-7

METEOROLOGICAL AND SOURCE INPUTS FOR A SLOW BURN ON THE PAD OF A TITAN III C VEHICLE - FALL METEOROLOGICAL REGIME

Parameter	Units	Layer						
		1	2	3	4	5	6	7
Q_K	ppm m^{-1}	6.36×10^4	5.20×10^5	3.07×10^6	8.60×10^6	1.57×10^7	2.59×10^7	3.84×10^7
z_R	m	18						
$\bar{u}_R$	m sec^{-1}	4.7						
$\sigma_{AR}\{\tau_{oK}\}$	deg	12.0						
σ_{ER}	deg	6.6						
τ_{oK}	sec	600	600	600	600	600	600	600
τ_K	sec	600	600	600	600	600	600	600
$\sigma_{ATK}\{\tau_{oK}\}$	deg	9.41	8.78	8.42	8.29	8.18	8.08	8.00
$\sigma_{ABK}\{\tau_{oK}\}$	deg	14.98	9.41	8.78	8.42	8.29	8.18	8.08
$\sigma_{yo}\{K\}$	m	34.9	81.4	127.9	162.8	186.0	209.3	255.8
α_K		1	1	1	1	1	1	1
σ_{ETK}	deg	5.18	4.83	4.63	4.56	4.50	4.45	4.40
σ_{EBK}	deg	8.24	5.18	4 83	4.63	4.56	4.50	4.45
$\sigma_{zo}\{K\}$	m	57.7	57.7	57.7	28.9	28.9	28.9	28.9
$\sigma_{xo}\{K\}$	m	34.9	81.4	127.9	162.8	186.0	209.3	255.8

TABLE B-7 (Continued)

Parameter	Units	Layer						
		1	2	3	4	5	6	7
β_K		1	1	1	1	1	1	1
z_{TK}	m	200	400	600	700	800	900	1000
z_{BK}	m	2	200	400	600	700	800	900
$\bar{u}_{TK}$	m sec^{-1}	5.97	6.39	6.65	6.76	6.85	6.93	7.00
$\bar{u}_{BK}$	m sec^{-1}	3.78	5.97	6.39	6.65	6.76	6.85	6.93
θ_{TK}	deg	95.8	101.6	107.4	110.3	113.2	116.1	119.0
θ_{BK}	deg	90.0	95.8	101.6	107.4	110.3	113.2	116.1
Φ_{TK}	^{o}K	298.6	299.1	299.3	299.5	299.8	299.9	299.9
Φ_{BK}	^{o}K	297.9	298.6	299.1	299.3	299.5	299.8	299.9
T_{TK}	^{o}K	297.7	296.2	294.2	293.4	292.7	291.7	290.7
T_{BK}	^{o}K	299.0	297.7	296.2	294.2	293.4	292.7	291.7
P_{TK}	mb	990	967	944	930	920	908	898
P_{BK}	mb	1013	990	967	944	930	920	908
t*	sec	1	1	1	1	1	1	1
Model No.		5	5	5	5	5	5	5

TABLE B-8

METEOROLOGICAL AND SOURCE INPUTS FOR A SLOW BURN ON THE PAD OF A TITAN III C VEHICLE - SPRING METEOROLOGICAL REGIME

Parameter	Units	Layer									
		1	2	3	4	5	6	7	8	9	10
Q_K	ppm m^{-1}	5.66 x 10^4	4.32 x 10^5	2.47 x 10^6	9.76 x 10^6	2.66 x 10^7	5.00 x 10^7	6.49 x 10^7	5.82 x 10^7	3.60 x 10^7	1.54 x 10^7
z_R	m	18									
$\bar{u}_R$	m sec^{-1}	6									
$\sigma_{AR}\{\tau_{oK}\}$	deg	7									
σ_{ER}	deg	3.8									
τ_{oK}	sec	600	600	600	600	600	600	600	600	600	600
τ_K	sec	600	600	600	600	600	600	600	600	600	600
$\sigma_{ATK}\{\tau_{oK}\}$	deg	6.25	6.04	5.93	5.85	5.79	5.74	5.70	5.66	5.63	5.60
$\sigma_{ABK}\{\tau_{oK}\}$	deg	7.77	6.25	6.04	5.93	5.85	5.79	5.74	5.70	5.66	5.63
$\sigma_{yo}\{K\}$	m	34.9	81.4	127.9	174.4	220.9	267.4	314.0	360.5	407.0	393.0
α_K		1	1	1	1	1	1	1	1	1	1
σ_{ETK}	deg	3.39	3.28	3.22	3.17	3.14	3.11	3.09	3.07	3.06	3.04
σ_{EBK}	deg	4.14	3.39	3.28	3.22	3.17	3.14	3.11	3.09	3.07	3.06
$\sigma_{zo}\{K\}$	m	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7
$\sigma_{xo}\{K\}$	m	34.9	81.4	127.9	174.4	220.9	267.4	314.0	360.5	407.0	393.0

TABLE B-8 (Continued)

Parameter	Units	Layer									
		1	2	3	4	5	6	7	8	9	10
β_K		1	1	1	1	1	1	1	1	1	1
z_{TK}	m	200	400	600	800	1000	1200	1400	1600	1800	2000
z_{BK}	m	2	200	400	600	800	1000	1200	1400	1600	1800
$\bar{u}_{TK}$	m sec^{-1}	6.72	6.95	7.08	7.18	7.26	7.32	7.37	7.42	7.46	7.50
$\bar{u}_{BK}$	m sec^{-1}	5.41	6.72	6.95	7.08	7.18	7.26	7.32	7.37	7.42	7.46
θ_{TK}	deg	108	116	124	132	140	148	156	164	172	180
θ_{BK}	deg	100	108	116	124	132	140	148	156	164	172
Φ_{TK}	^oK	299.6	299.9	300.4	301.1	301.6	302.0	302.5	302.9	302.9	303.5
Φ_{BK}	^oK	298.9	299.6	299.9	300.4	301.1	301.6	302.0	302.5	302.9	303.5
T_{TK}	^oK	298.7	297.0	295.5	294.0	292.5	290.7	289.2	287.5	285.7	284.2
T_{BK}	^oK	300.0	298.7	297.0	295.5	294.0	292.5	290.7	289.2	287.5	285.7
P_{TK}	mb	990	967	944	920	898	875	855	835	815	795
P_{BK}	mb	1013	990	967	944	920	898	875	855	835	815
t*	sec	1	1	1	1	1	1	1	1	1	1
Model No.		5	5	5	5	5	5	5	5	5	5

TABLE B-9

METEOROLOGICAL AND SOURCE INPUTS FOR A SLOW BURN ON THE PAD OF A TITAN III C VEHICLE - SEA-BREEZE METEOROLOGICAL REGIME

Parameter	Units	Layer						
		1	2	3	4	5	6	7
Q_K	ppm m^{-1}	5.24×10^4	1.73×10^5	6.16×10^5				
z_R	m	18						
$\bar{u}_R$	m sec^{-1}	4.5						
$\sigma_{AR}\{\tau_{oK}\}$	deg	12						
σ_{ER}	deg	6.6						
τ_{oK}	sec	600	600	600				
τ_K	sec	491	491	491				
$\sigma_{ATK}\{\tau_{oK}\}$	deg	7.62	6.35	5.70				
$\sigma_{ABK}\{\tau_{oK}\}$	deg	21.5	7.62	6.35				
$\sigma_{yo}\{K\}$	m	23.3	46.5	69.8				
α_K		1	1	1				
σ_{ETK}	deg	100	200	300				
σ_{EBK}	deg	2	100	200				
$\sigma_{zo}\{K\}$	m	7.09	8.53	9.5				
$\sigma_{xo}\{K\}$	m	2.51	7.09	8.53				

TABLE B-9 (Continued)

Parameter	Units	Layer						
		1	2	3	4	5	6	7
β_K		1	1	1				
z_{TK}	m	100	200	300				
z_{BK}	m	2	100	200				
$\bar{u}_{TK}$	m sec^{-1}	7.09	8.53	9.5				
$\bar{u}_{BK}$	m sec^{-1}	2.51	7.09	8.53				
θ_{TK}	deg	143.3	146.7	150				
θ_{BK}	deg	140	143.3	146.7				
Φ_{TK}	^oK	293.7	294.0	294.2				
Φ_{BK}	^oK	292.9	293.7	294.0				
T_{TK}	^oK	293.7	293.2	292.2				
T_{BK}	^oK	294.0	293.7	293.2				
P_{TK}	mb	1000	990	977				
P_{BK}	mb	1013	1000	990				
t*	sec	1	1	1				
Model No.		5	5	5				

TABLE B-10

METEOROLOGICAL AND SOURCE INPUTS FOR A SINGLE-ENGINE ON-PAD BURN OF A TITAN III C VEHICLE - FALL METEOROLOGICAL REGIME

Parameter	Units	Layer						
		1	2	3	4	5	6	7
Q_K	ppm m^{-1}	8.50×10^4	5.70×10^5	2.82×10^6	7.01×10^6	1.17×10^7	1.78×10^7	2.43×10^7
z_R	m	18						
$\bar{u}_R$	m sec^{-1}	4.7						
$\sigma_{AR}\{\tau_{oK}\}$	deg	12.0						
σ_{ER}	deg	6.6						
τ_{oK}	sec	600	600	600	600	600	600	600
τ_K	sec	458	458	458	458	458	458	458
$\sigma_{ATK}\{\tau_{oK}\}$	deg	9.41	8.78	8.42	8.29	8.18	8.08	8.00
$\sigma_{ABK}\{\tau_{oK}\}$	deg	14.98	9.41	8.78	8.42	8.29	8.18	8.08
$\sigma_{yo}\{K\}$	m	55.1	101.6	148.1	183.0	206.3	229.5	252.8
α_K		1	1	1	1	1	1	1
σ_{ETK}	deg	5.18	4.83	4.63	4.56	4.50	4.45	4.40
σ_{EBK}	deg	8.24	5.18	4.83	4.63	4.56	4.50	4.45
$\sigma_{zo}\{K\}$	m	57.7	57.7	57.7	28.9	28.9	28.9	28.9
$\sigma_{xo}\{K\}$	m	55.1	101.6	148.1	183.0	206.3	229.5	252.8

TABLE B-10(Continued)

Parameter	Units	Layer						
		1	2	3	4	5	6	7
β_K		1	1	1	1	1	1	1
z_{TK}	m	200	400	600	700	800	900	1000
z_{BK}	m	2	200	400	600	700	800	900
$\bar{u}_{TK}$	m sec^{-1}	5.97	6.39	6.65	6.76	6.85	6.93	7.00
$\bar{u}_{BK}$	m sec^{-1}	3.78	5.97	6.39	6.65	6.76	6.85	6.93
θ_{TK}	deg	95.8	101.6	107.4	110.3	113.2	116.1	119.0
θ_{BK}	deg	90.0	95.8	101.6	107.4	110.3	113.2	116.1
Φ_{TK}	^{o}K	298.6	299.1	299.3	299.5	299.8	299.9	299.9
Φ_{BK}	^{o}K	297.9	298.6	299.1	299.3	299.5	299.8	299.9
T_{TK}	^{o}K	297.7	296.2	294.2	293.4	292.7	291.7	290.7
T_{BK}	^{o}K	299.0	297.7	296.2	294.2	293.4	292.7	291.7
P_{TK}	mb	990	967	944	930	920	908	898
P_{BK}	mb	1013	990	967	944	930	920	908
t*	sec	1	1	1	1	1	1	1
Model No.		5	5	5	5	5	5	5

TABLE B-11

METEOROLOGICAL AND SOURCE INPUTS FOR A SINGLE-ENGINE ON-PAD BURN OF A TITAN III C VEHICLE - SPRING METEOROLOGICAL REGIME

Parameter	Units	Layer									
		1	2	3	4	5	6	7	8	9	10
Q_K	ppm m^{-1}	1.05×10^5	7.55×10^5	3.81×10^6	1.24×10^7	2.60×10^7	3.52×10^7	3.08×10^7	1.74×10^7	6.36×10^6	1.49×10^6
z_R	m	18									
$\bar{u}_R$	m sec^{-1}	6									
$\sigma_{AR}\{\tau_{oK}\}$	deg	7									
σ_{ER}	deg	3.8									
τ_{oK}	sec	600	600	600	600	600	600	600	600	600	600
τ_K	sec	463	463	463	463	463	463	463	463	463	463
$\sigma_{ATK}\{\tau_{oK}\}$	deg	6.25	6.04	5.93	5.85	5.79	5.74	5.70	5.66	5.63	5.60
$\sigma_{ABK}\{\tau_{oK}\}$	deg	7.77	6.25	6.04	5.93	5.85	5.79	5.74	5.70	5.66	5.63
$\sigma_{yo}\{K\}$	m	55.1	101.6	148.1	194.7	241.2	287.7	334.2	306.3	259.8	213.3
α_K		1	1	1	1	1	1	1	1	1	1
σ_{ETK}	deg	3.39	3.28	3.22	3.17	3.14	3.11	3.09	3.07	3.06	3.04
σ_{EBK}	deg	4.14	3.39	3.28	3.22	3.17	3.14	3.11	3.09	3.07	3.06
$\sigma_{zo}\{K\}$	m	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7
$\sigma_{xo}\{K\}$	m	55.1	101.6	148.1	194.7	241.2	287.7	334.2	306.3	259.8	213.3

TABLE B-11 (Continued)

Parameter	Units	Layer									
		1	2	3	4	5	6	7	8	9	10
β_K		1	1	1	1	1	1	1	1	1	1
z_{TK}	m	200	400	600	800	1000	1200	1400	1600	1800	2000
z_{BK}	m	2	200	400	600	800	1000	1200	1400	1600	1800
$\bar{u}_{TK}$	m sec^{-1}	6.72	6.95	7.08	7.18	7.26	7.32	7.37	7.42	7.46	7.50
$\bar{u}_{BK}$	m sec^{-1}	5.41	6.72	6.95	7.08	7.18	7.26	7.32	7.37	7.42	7.46
θ_{TK}	deg	108	116	124	132	140	148	156	164	172	180
θ_{BK}	deg	100	108	116	124	132	140	148	156	164	172
Φ_{TK}	^{o}K	299.6	299.9	300.4	301.1	301.6	302.0	302.5	302.9	302.9	303.5
Φ_{BK}	^{o}K	298.9	299.6	299.9	300.4	301.1	301.6	302.0	302.5	302.9	303.5
T_{TK}	^{o}K	298.7	297.0	295.5	294.0	292.5	290.7	289.2	287.5	285.7	284.2
T_{BK}	^{o}K	300.0	298.7	297.0	295.5	294.0	292.5	290.7	289.2	287.5	285.7
P_{TK}	mb	990	967	944	920	898	875	855	835	815	795
P_{BK}	mb	1013	990	967	944	920	898	875	855	835	815
t*	sec	1	1	1	1	1	1	1	1	1	1
Model No.		5	5	5	5	5	5	5	5	5	5

TABLE B-12

METEOROLOGICAL AND SOURCE INPUTS FOR A SINGLE-ENGINE ON-PAD BURN OF A TITAN III C VEHICLE - SEA-BREEZE METEOROLOGICAL REGIME

Parameter	Units	Layer						
		1	2	3	4	5	6	7
Q_K	ppm m^{-1}	1.13×10^5	3.41×10^5	1.11×10^6				
z_R	m	18						
$\bar{u}_R$	m sec^{-1}	4.5						
$\sigma_{AR}\{\tau_{oK}\}$	deg	12						
σ_{ER}	deg	6.6						
τ_{oK}	sec	600	600	600				
τ_K	sec	317	317	317				
$\sigma_{ATK}\{\tau_{oK}\}$	deg	7.62	6.35	5.70				
$\sigma_{ABK}\{\tau_{oK}\}$	deg	21.5	7.62	6.35				
$\sigma_{yo}\{K\}$	m	43.5	66.7	90.0				
α_K		1	1	1				
σ_{ETK}	deg	4.18	3.48	3.12				
σ_{EBK}	deg	11.84	4.18	3.48				
$\sigma_{zo}\{K\}$	m	28.9	28.9	28.9				
$\sigma_{xo}\{K\}$	m	43.5	66.7	90.0				

TABLE B-12 (Continued)

Parameter	Units	Layer						
		1	2	3	4	5	6	7
β_K		1	1	1				
z_{TK}	m	100	200	300				
z_{BK}	m	2	200	300				
$\bar{u}_{TK}$	m sec^{-1}	7.09	8.53	9.5				
$\bar{u}_{BK}$	m sec^{-1}	2.51	7.09	8.53				
θ_{TK}	deg	143.3	146.7	150				
θ_{BK}	deg	140	143.3	146.7				
Φ_{TK}	^oK	293.7	294.0	294.2				
Φ_{BK}	^oK	292.9	293.7	294.0				
T_{TK}	^oK	293.7	293.2	292.2				
T_{BK}	^oK	294.0	293.7	293.2				
P_{TK}	mb	1000	990	977				
P_{BK}	mb	1013	1000	990				
t*	sec	1	1	1				
Model No.		5	5	5				

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