Appendix G

NASA Report: Evaluation of Taurus II Static Test Firing and Normal Launch Rocket Plume Emissions

Report No. 09-640/5-01

Evaluation of Taurus II Static Test Firing and Normal Launch Rocket Plume Emissions

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1. INTRODUCTION

The Taurus II launch vehicle is being designed and built by Orbital Sciences Corporation with the objective of launching missions from Wallops Flight Facility (WFF) to service the International Space Station. This report presents the findings of rocket exhaust plume emission and atmospheric dispersion analyses performed for the Taurus II first stage using a large archive of WFF weather balloon soundings. The report also explains the development of input data, describes the basic features of the modeling tools and identifies the assumptions made to support the analyses.

The Taurus II first stage uses liquid propellants commonly found in other modern U.S. built rockets. The first stage fuel is a refined form of kerosene known as RP-1 and the oxidizer is liquid oxygen (LOX). Although these propellants are burned in a fuel rich mixture the exhaust products can be considered environmentally friendly compared to solid propellant exhaust. The use of RP-1/LOX also avoids handling and spill toxic hazards associated with liquid hypergolic propellants. Consequently, the primary chemical exhaust constituent of concern from a toxicity standpoint is carbon monoxide (CO). The hazard associated with exposure to CO can be associated with several industry standard exposure criteria. Since rocket emissions from static test firings or rocket launches are relatively short duration events that only occur a few times a year over the course of the program, short duration or emergency exposure standards are more appropriate than long duration exposure standards designed for work place environments. One such emergency exposure standard is the National Institute for Occupational Safety and Health (NIOSH) definition of the Immediately Dangerous to Life or Health (IDLH) exposure threshold for an airborne chemical. The IDLH is intended to be used in conjunction with workers wearing respirators in contaminated areas, such that if the respirator fails the person could escape the contaminated area without being incapacitated given a maximum exposure of 30 minutes. Perhaps a more appropriate set of exposure guidelines are the Acute Exposure Guideline Levels (AEGLs) that are supported by the EPA. The development of Acute Exposure Guideline Levels (AEGLs) is a collaborative effort of the public and private sectors worldwide. AEGLs are intended to describe the risk to humans resulting from once-in-a-lifetime, or rare, exposure to airborne chemicals. The National Advisory Committee for the Development of Acute Exposure Guideline Levels for Hazardous Substances (AEGL Committee) is involved in developing these guidelines to help both national and local authorities, as well as private companies, deal with emergencies involving spills, or other catastrophic exposures. The recommended interim AEGLs for carbon monoxide are listed in Table 1-1.

Table 1-1: Interim Acute Exposure Guideline Levels (AEGLs) for Carbon Monoxide.

AEGL Level	10 min Exposure [ppm]	30 min Exposure [ppm]	60 min Exposure [ppm]	4 hr Exposure [ppm]
AEGL 1	NR	NR	NR	NR
AEGL 2	420	150	83	33
AEGL 3	1700	600	330	150

NR = No exposure level recommended due to insufficient or inconclusive data.

Definitions of the AEGL levels are as follows:

AEGL-1 is the airborne concentration, expressed as parts per million or milligrams per cubic meter (ppm or mg/m3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic nonsensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.

AEGL-2 is the airborne concentration (expressed as ppm or mg/m3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.

AEGL-3 is the airborne concentration (expressed as ppm or mg/m3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.

The time duration that a receptor is exposed to a rocket exhaust plume emission depends upon the cloud transport wind speed and the size of the cloud. The cloud or plume grows in size as it transports downwind. Typical exposure durations are estimated to be in the 10 to 30 minute range but may approach one hour under very light wind conditions.

The report authors do not have toxicological expertise regarding hazardous CO thresholds for flora and fauna that may be of environmental concern. The selection of the most appropriate exposure level to apply to exposed flora and fauna is left to the judgment of others. It is however noted here that the vast majority of emission scenarios evaluated in this study predict far field maximum ground level CO concentrations below 10 parts per million (ppm), which is quite benign relative to all published human hazardous thresholds.

There are two emission scenarios of concern for the Taurus II environmental assessment:

1. Static test firing of the first stage while the stacked vehicle is held stationary on the launch pad. In this scenario the two first stage engines are both ignited and are run through a 52 second thrust profile that ramps the engines up to full performance (112.9%) and back down. Exhaust from the rocket engine nozzles is directed downward into a flame trench and deflected through the flame duct such that the exhaust gases are diverted away from the launch vehicle and nearby facilities. The exhaust plume exits the flame duct at supersonic velocity and the flow is approximately parallel to and slightly above the ground.

2. Normal launch of the Taurus II vehicle. In this scenario a fully configured launch vehicle with payload is ignited on the launch pad at time T-0. The vehicle is held on the pad for approximately 2 seconds as the first stage engines build thrust and then hold-downs are released allowing the vehicle to begin ascent to orbit. During ascent the vehicle velocity steadily increases resulting in a time and altitude varying exhaust product emission rate. Initially the rocket engine exhaust is largely directed into and through the flame duct. As the vehicle lifts off from the pad and clears the launch tower, a portion of the exhaust plume impinges on the pad structure and is directed radially around the launch pad stand. The portion of the rocket plume that interacts with the launch pad and flame trench is referred to as the "ground cloud". As the vehicle climbs to several hundred feet above the pad, the rocket plume reaches a point where the gases no longer interact with the ground surface and the exhaust plume is referred to as the "contrail cloud".

The concepts of the ground and contrail clouds are illustrated in Figure 1-1 using a Titan IV launch from Cape Canaveral as an example. For atmospheric dispersion analyses of rocket emissions that could affect receptors on the ground, it has been standard practice at the Federal Ranges (Cape Canaveral and Vandenberg Air Force Base) to simulate the emissions from the ascending launch vehicle from the ground to a vehicle altitude of approximately 3000 meters. The operational toxic dispersion analysis tool used by the Federal Ranges for launch support and public risk assessment is Version 7.13 of the Rocket Exhaust Effluent Diffusion Model (REEDM). This same computer program was used to perform the dispersion analyses for the Taurus II emission scenarios. The features of REEDM pertinent to this study are discussed in the next section.

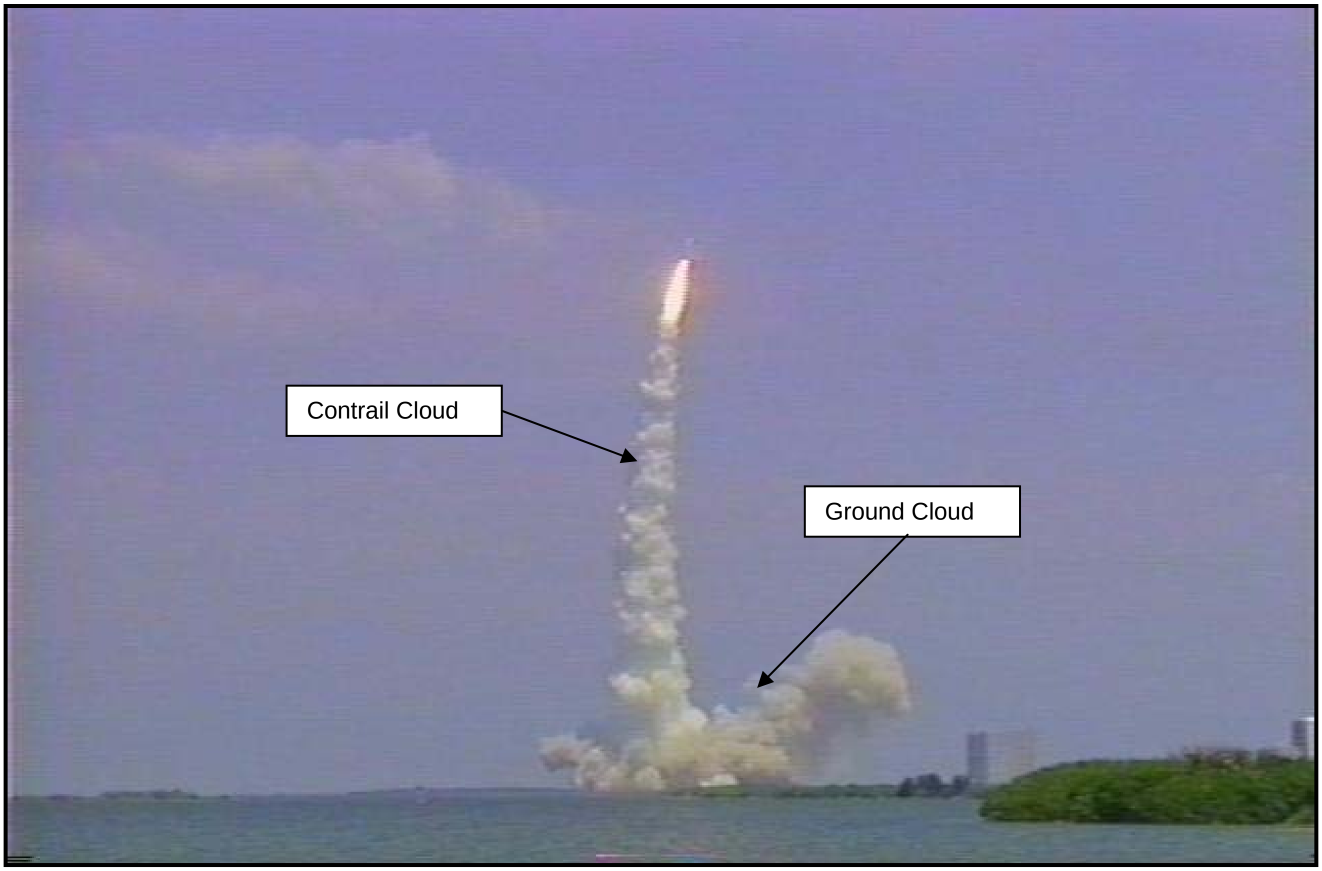

Figure 1-1. Illustration of the Ground Cloud and Contrail Cloud Portions of a Titan IV Rocket Emission Plume Associated With Normal Vehicle Launch.

2. THE ROCKET EXHAUST EFFLUENT DISPERSION MODEL (REEDM)

REEDM is a toxic dispersion model specifically tailored to address the large buoyant source clouds generated by rocket launches, test firings and catastrophic launch vehicle explosions. Under ongoing Air Force support, REEDM evolved from the NASA Multi-Layer Diffusion Model, which was written initially to evaluate environmental effects associated with the Space Shuttle, and has been generalized to handle a wide variety of launch vehicle types and propellant combinations. REEDM falls in the category of "Gaussian puff" atmospheric dispersion models in that the initial mass distribution of toxic materials within the cloud at the time the cloud reaches thermal stabilization height in the atmosphere is assumed to be normally distributed. By making the Gaussian mass distribution assumption, the differential equation defining mass diffusion can be solved in closed form using exponential functions and may be readily implemented in a fast running computer program. Gaussian puff models are still widely used by the EPA for environmental and permitting studies, by Homeland Security and the Defense Threat Reduction Agency for assessment of chemical, biological and radiological materials, and by the petrochemical industry for accidental releases of industrial chemicals.

REEDM processing of an emission event can be partitioned into the following basic steps:

1. Acquire and process vehicle related data from an input vehicle database file.

2. Acquire and process meteorological data, which in this study is a combination of archived weather balloon soundings used in conjunction with an internal REEDM climatological turbulence algorithm.

3. Acquire the chemical composition and thermodynamic properties of the rocket exhaust emissions and define the initial size, shape, location and heat content of the exhaust cloud (herein referred to as the "source term" or "source cloud"). REEDM has an internal propellant equilibrium combustion model that is used to compute these terms for vehicle catastrophic failure modes but for normal launch and static test firing scenarios this data is calculated external to REEDM and placed in the vehicle database file read by REEDM.

4. Iteratively calculate the buoyant cloud rise rate and cloud growth rate to achieve a converged estimate of the cloud stabilization height above ground, size and downwind position. The cloud rise equations evaluate both cloud thermodynamic state as well as the local atmospheric stability, which is defined by the potential temperature lapse rate.

5. Partition the stabilized cloud into disks and mark whether or not part of the stabilized cloud is above a capping atmospheric temperature inversion. Inversions (or other sufficiently stable air masses) act as a barrier to gaseous mixing and are treated in REEDM as reflective boundaries.

6. Transport the cloud disks downwind and grow the disk size using climatologic model estimates of atmospheric turbulence intensity. Turbulence intensity is a function of wind speed and solar radiation intensity. Turbulence varies with time of day and cloud cover conditions because these influence the solar radiation intensity.

7. Calculate concentrations at ground receptor points and determine the plume or cloud track "centerline" that defines the peak concentration as a function of downwind distance. Concentration at any given receptor point is computed as the sum of exposure contributions from each cloud disk. Concentration is solved using the closed form Gaussian dispersion equation and accounts for the effect of ground and capping inversion reflections.

8. Report concentration centerline values in table format as a function of distance from the source origin (e.g. launch pad)

There are other features and submodels of REEDM that are more fully described in the REEDM technical description manual and will not be reviewed in this report.

There are several important assumptions made in REEDM that have a bearing on this Environmental Assessment study. REEDM was designed to primarily predict hazard conditions downwind from the stabilized exhaust cloud. REEDM does not directly calculate or report cloud concentrations during the buoyant cloud rise phase, however, advanced model users can extract sufficient pertinent cloud data from internal calculations to derive concentration estimates during the cloud rise phase manually. One assumption that REEDM makes about the nature and behavior of a rocket exhaust cloud is that it can be initially defined as a single cloud entity that grows and moves but remains as a single cloud during the formation and cloud rise phases. A consequence of this assumption is that once the cloud lifts off the ground during the buoyant cloud rise phase, there will be no predicted cloud chemical concentration on the ground immediately below the cloud. Ground level concentrations will be predicted to remain at zero ppm until the some of the elevated cloud material is eventually brought back down to ground level by mixing due to atmospheric turbulence. This concept is illustrated in Figure 2-1 and it is noted that REEDM is designed to report concentrations downwind from the stabilized cloud position. The region downwind from the stabilized exhaust cloud is referred to as the "far field". It is also noted here that the most concentrated part of these rocket exhaust clouds remains at an altitude well above the ground level. REEDM is not able to model stochastic uncertainty in the source cloud and atmospheric flow such that if a gust of wind, small turbulence eddy or nuance of the launch pad flame duct structure causes a small portion of the main exhaust cloud to detach from the main cloud, the model will not correctly predict the transport, dispersion or concentration contribution from the detached cloud material. Likewise if there are strong atmospheric updrafts or down drafts, such as associated with development of thunderstorm cells or towering cumulus clouds, REEDM will not correctly model strong vertical displacements of the entire exhaust cloud or strong shearing forces that may completely breakup the cloud under such conditions (these are not favorable conditions for launch either and a planned launch would never be conducted with strong thunderstorm and cloud development activity in the launch area).

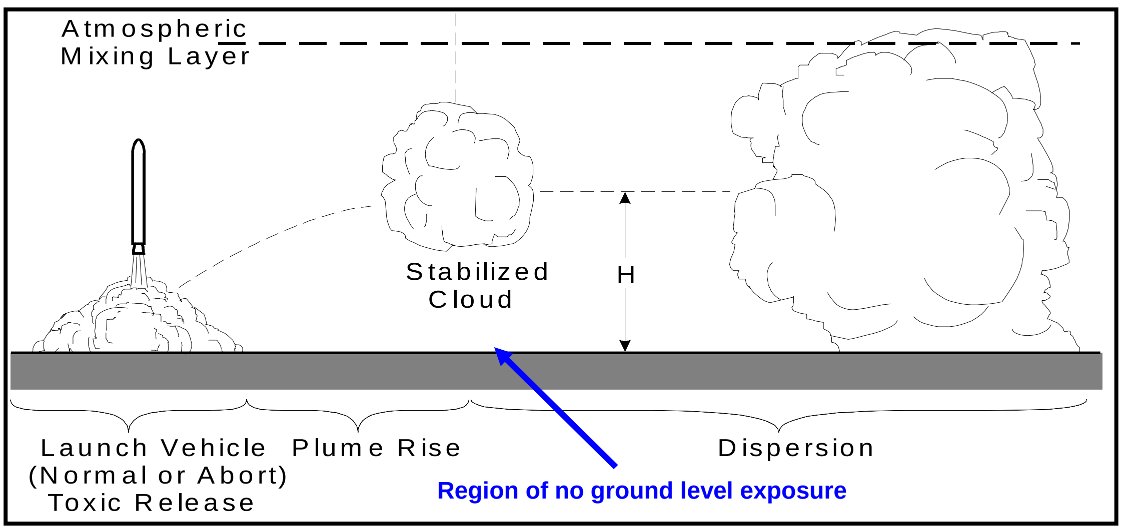

Figure 2-1. Conceptual Illustration of Rocket Exhaust Source Cloud Formation, Cloud Rise and Cloud Atmospheric Dispersion.

REEDM is also somewhat constrained by the Gaussian assumptions inherent in the model that require a single average transport wind speed and direction. The portion of the atmosphere selected for averaging the transport winds has been improved over the years of operational use at the Air Force ranges. Old versions of REEDM averaged the winds over the entire boundary layer, which in the absence of a capping inversion, was treated as being 3000 meters deep. The modern version of REEDM now selects the appropriate atmospheric layer based on the stabilization height of the cloud, the top of the cloud and the location of the reflective boundary layers. Comparison of REEDM predicted rocket exhaust cloud transport direction and speed with Doppler weather radar tracks of rocket exhaust clouds has indicated that the modern version of REEDM performs very satisfactorily in predicting the correct average cloud transport direction and speed. The “multi-layer” aspect of REEDM is still retained from its early development and refers to the partitioning of the stabilized rocket exhaust cloud into “disks” of cloud material assigned to meteorological levels at different altitudes. The altitude bands are typically 20 to 50 meters in depth. REEDM models the initial formation of a rocket exhaust cloud as either an ellipsoid or a sphere and predicts the buoyant could rise of the source as a single cloud entity. Once the cloud is predicted to have achieved a condition of thermal stability in the atmosphere, the cloud is partitioned into disks. The placement of each disk relative to the source origin (e.g. the launch pad) is determined based on the rise time of the cloud through a sequence of meteorological layers that are defined using the measurement levels obtained from a mandatory weather balloon input data file. Each meteorological layer may have a unique wind speed and direction that displaces the cloud disk in the down wind direction. The initial placement of cloud disks that are associated with the lower portion of the overall source cloud are not influenced by winds above their stabilized altitude level whereas disks near the top of the stabilized cloud will be displaced by the winds all the way from the ground level to the disk stabilization altitude. Thus the vertical stack of cloud disks can be displaced relative to each other due to the influence of wind speed and direction shears. The concept of the stabilized cloud partition into disks is illustrated in Figure 2-2.

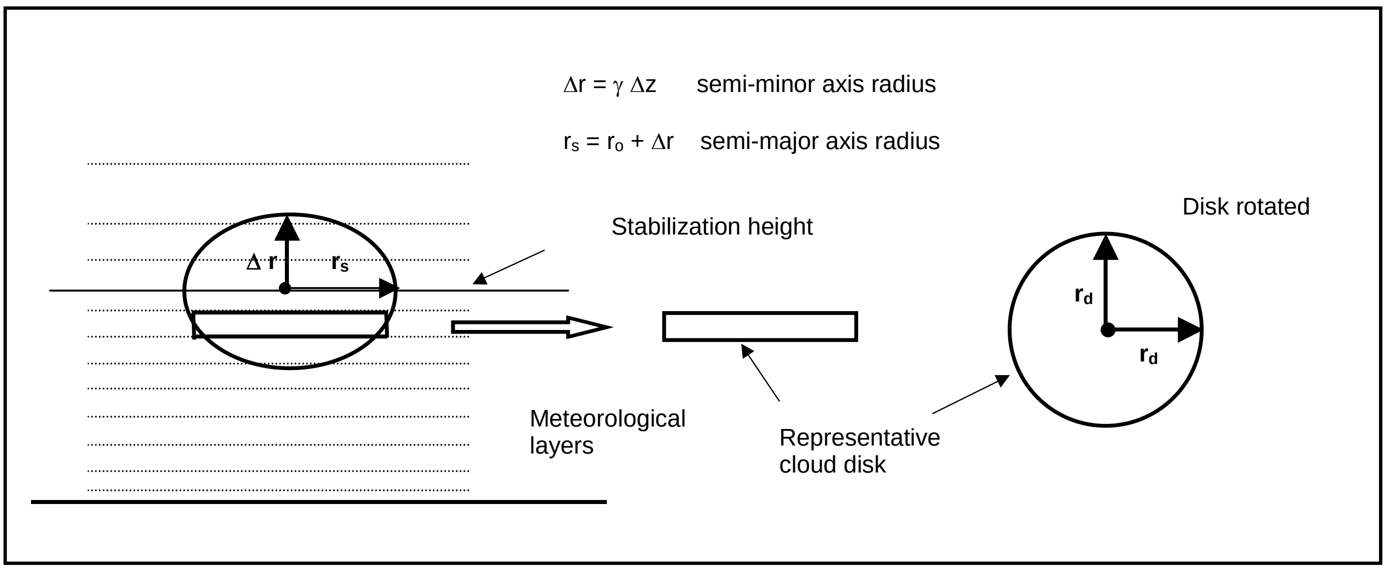

Figure 2-2. Illustration of REEDM Partitioning a Stabilized Cloud into Disks.

Once the cloud disks positions are initialized, future downwind transport applies the same average atmospheric boundary layer transport wind speed and direction to each cloud disk as illustrated in Figure 2-3.

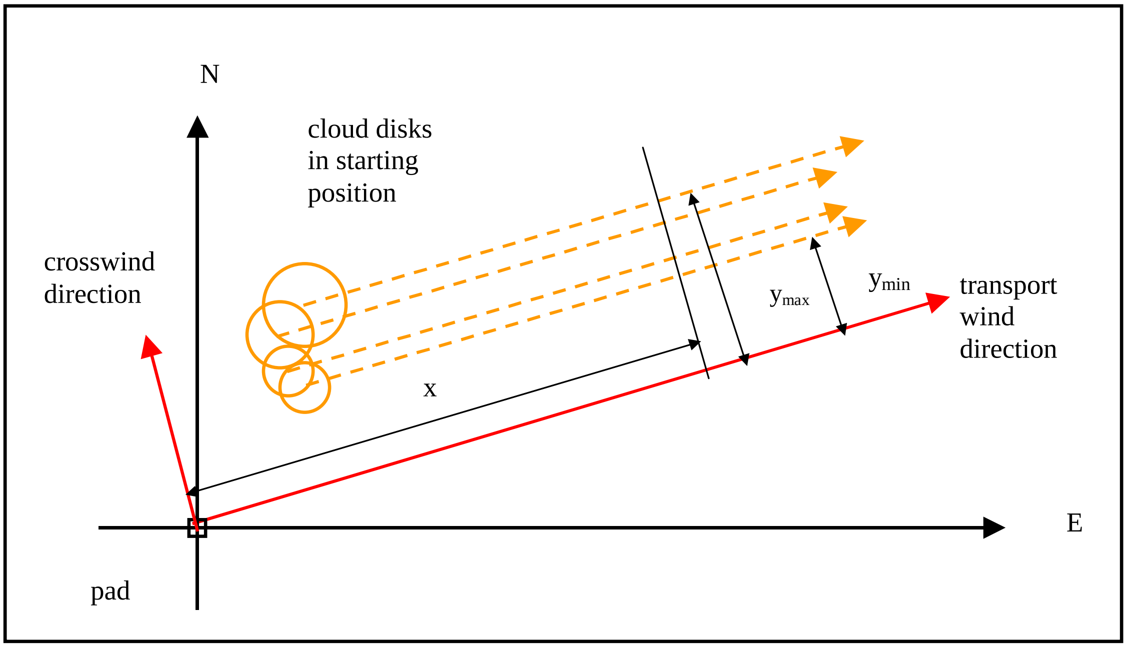

Figure 2-3. Illustration of Straight Line Transport of Stabilized Exhaust Cloud Disks Using Average Mixing Layer Wind Speed and Direction.

The assumption of straight-line transport used in REEDM during the cloud transport and dispersion phase ignores the possibility of complex wind fields that might arise in mountainous terrain or that could evolve during passage of a seabreeze front or synoptic scale weather front. It is recommended that the assumption of uniform winds be limited to plume transport distances of less that 20 kilometers. As will be shown in the analysis results section, REEDM predicted typical ranges of 5 to 10 kilometers from the launch pad to the location of the maximum far field ground level CO concentration point, thus the assumption of straight line transport should not be a problem.

In both Taurus II scenarios the exhaust emissions from the rocket combustion are at several thousand degrees Kelvin and are highly buoyant. The high temperature of these exhaust emissions causes the plume to be less dense than the surrounding atmosphere and buoyancy forces acting on the cloud cause it to lift off the ground and accelerate vertically. As the buoyant cloud rises, it entrains ambient air and grows in size while also cooling. In this initial cloud rise phase, the growth of the cloud volume is due primarily to internal velocity gradients and mixing induced by large temperature gradients within the cloud itself. Even though the cloud is entraining air and cooling by virtue of mixing hot combustion gases with cooler ambient air, the net thermal buoyancy in the cloud is conserved and the cloud will continue to rise until it either reaches a stable layer in the atmosphere or the cloud vertical velocity becomes slow enough to be damped by viscous forces. REEDM applies the following solution of Newton's second law of motion to a buoyant cloud in the atmosphere to iteratively predict cloud stabilization height:

$$z(t) = \left[\frac{3F_m}{u\gamma^2\sqrt{s}} \sin\left(t\sqrt{s}\right) + \frac{3F_c}{u\gamma^2 s}\left(1 - \cos\left(t\sqrt{s}\right)\right) + \left(\frac{r_o}{\gamma}\right)^3 \right]^{1/3} - \frac{r_o}{\gamma}$$

where:

s = atmospheric stability parameter = $\dfrac{g}{\theta_a} \dfrac{\Delta\theta_a}{\Delta Z}$ [sec^{-2}]

g = gravitational acceleration constant = 9.81 [m/sec^2]

θ_a = potential temperature of ambient air [K]

F_m = $r_o^2 w_o u$ = initial vertical momentum [m^4/sec^2]

u = mean ambient wind speed [m/sec]

w_o = initial vertical velocity [m/sec] (typically = 0.0)

r_o = initial plume cross-sectional radius [m]

F_c = initial buoyancy = $\dfrac{g\,\dot{q}}{\pi\,\rho_c\,C_p\,T_a}$ [m^4/s^3]

C_p = specific heat of exhaust cloud gases [cal/kg K]

γ = air entrainment coefficient (dimensionless)

z = plume height at time t [m]

$\dot{q}$ = initial plume heat flux [cal/sec]

T_a = ambient air temperature [K]

ρ_c = density of exhaust cloud gases [kg/m^3]

A critical parameter in the cloud rise equation is the rate of ambient air entrainment that is defined by the dimensionless air entrainment coefficient, γ. Cloud growth as a function of altitude is assumed to be linearly proportional and the air entrainment coefficient defines the constant of proportionality. REEDM's cloud rise equations have been compared with observations and measurements of Titan rocket ground clouds and a best-fit empirical cloud rise air entrainment coefficient has been derived from the test data, a sample of which is illustrated in Figure 2-4.

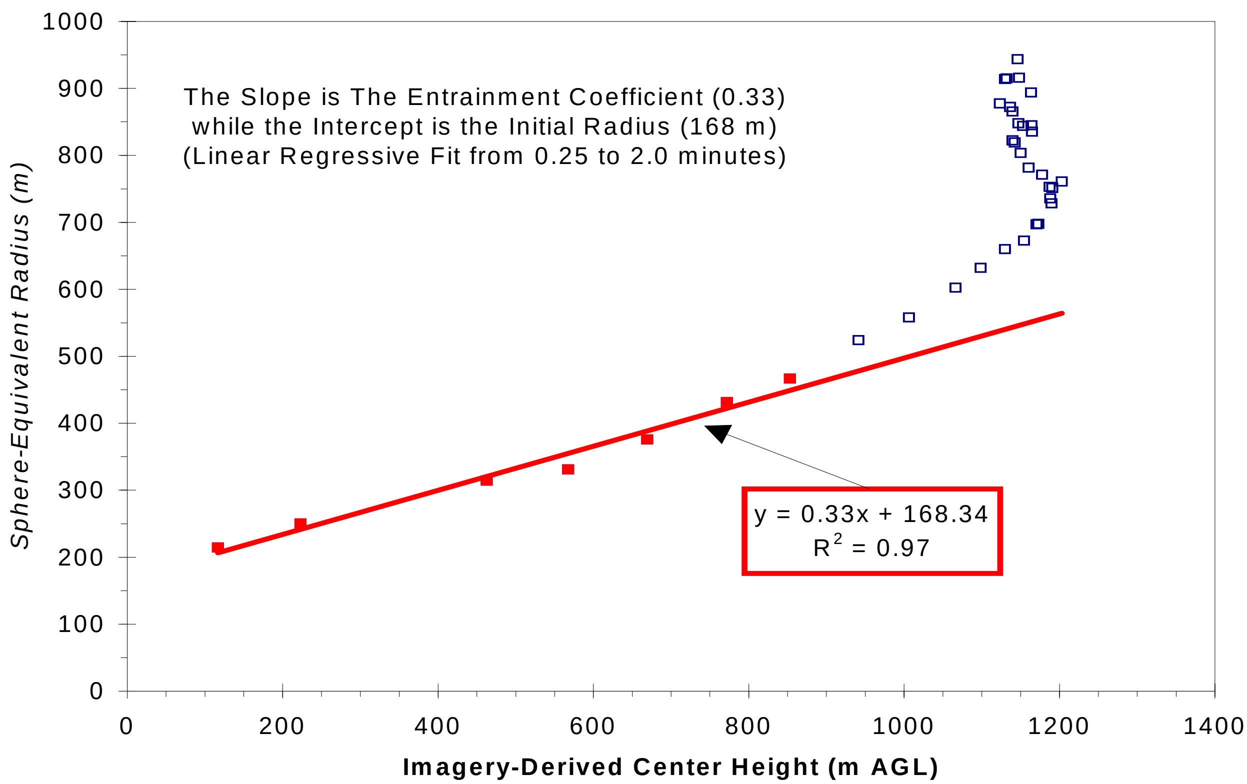

Figure 2-4. Observed Cloud Growth Versus Height for Titan IV A-17 Mission.

The Taurus II buoyant source clouds are predicted to rise from 500 to 1300 meters above the ground depending on atmospheric lapse rate conditions.

3. TAURUS II DATA DEVELOPMENT

Proper specification of vehicle characterization input data is critical to the overall toxic dispersion analysis problem. While many vehicle input parameters are straightforward and readily verifiable (e.g. types and amounts of propellants loaded on the vehicle), other parameters inherently involve greater uncertainty and are not readily verifiable (e.g. amount of ambient air entrained into the rocket plume at the flame duct inlet). In this report section the vehicle input data values used in the REEDM Taurus II normal launch and static test firing scenario analyses are itemized and explained. Input parameters that entail significant uncertainty were treated in a conservative fashion in the sense that choices were made to favor overestimating rather than underestimating the toxic chemical concentrations being evaluated for the Environmental Assessment study. Information pertaining to the vehicle propellant loads, burn rates and expected nominal launch flight trajectory were provided by WFF NASA or Orbital Sciences personnel and converted by ACTA into REEDM database format.

3.1 Normal Launch Vehicle Data

The following data items represent the vehicle data needed to characterize the normal launch scenario and are presented in the REEDM database format.

```
#05.00                       VEHICLE DATA SECTION
   VEHICLE TYPE = 4, NAME =     TAURUS-II,
   TIME HEIGHT COEFFICIENTS A,B,C =     0.967700,     0.471980,       2.2000,
#05.01 NORMAL LAUNCH ENGINE DATA FOR STAGES IGNITED AT LIFT-OFF:
   NUMBER OF IGNITED SRB'S           =   0,
   SOLID FUEL MASS             (LBM) =   0.0000000,
   SOLID FUEL BURN RATE      (LBM/S) =   0.0000000,
   LIQUID FUEL MASS            (LBM) =  142735.000,
   LIQUID FUEL BURN RATE     (LBM/S) =   645.90000,
   LIQUID OXIDIZER MASS        (LBM) =  390779.000,
   LIQUID OXIDIZER BURN RATE (LBM/S) =   1768.2000,
   AIR ENTRAINMENT RATE IN GROUND CLOUD       (LBM/S) =   0.0000000,
   TOTAL DELUGE WATER ENTRAINED IN GROUND CLOUD (LBM) =   0.0000000,
   AIR ENTRAINMENT RATE IN ROCKET CONTRAIL    (LBM/S) =   0.0000000,
   VEHICLE HEIGHT TO WHICH PLUME CONTRIBUTES TO GROUND CLOUD (FT) = 525,
   GROUND CLOUD INITIAL AVERAGE TEMPERATURE         (F) =  3487,
   GROUND CLOUD INITIAL HEAT CONTENT           (BTU/LBM) =  3475,
   INITIAL VERTICAL VELOCITY OF GROUND CLOUD     (FT/S) =   0.0,
   INITIAL RADIUS OF GROUND CLOUD                  (FT) = 160.0,
   INITIAL HEIGHT OF GROUND CLOUD                  (FT) =   0.0,
   INITIAL X DISPLACEMENT OF GROUND CLOUD FROM PAD (FT) =   0.0,
   INITIAL Y DISPLACEMENT OF GROUND CLOUD FROM PAD (FT) =   0.0,
   PLUME CONTRAIL INITIAL AVERAGE TEMPERATURE       (F) =  3487,
   PLUME CONTRAIL INITIAL HEAT CONTENT         (BTU/LBM) =  3475,
#05.02 NORMAL LAUNCH EXHAUST PRODUCT DATA:
 CHEMICAL NAME     MOL. WT.   MASS FRAC. GAS   MASS FRAC. COND  HAZARDOUS
 GROUND CLOUD:
   CO2              44.011        0.44824         0.00000          Y
   CO               28.011        0.25637         0.00000          Y
   H2O              18.015        0.28893         0.00000          N
```

```
  H2              2.016       0.00557       0.00000       N
  OH             17.007       0.00077       0.00000       N
  H               1.008       0.00006       0.00000       N
  O2             31.999       0.00005       0.00000       N
  O              15.999       0.00001       0.00000       N
  END
 CONTRAIL:
  CO2            44.011       0.44824       0.00000       Y
  CO             28.011       0.25637       0.00000       Y
  H2O            18.015       0.28893       0.00000       N
  H2              2.016       0.00557       0.00000       N
  OH             17.007       0.00077       0.00000       N
  H               1.008       0.00006       0.00000       N
  O2             31.999       0.00005       0.00000       N
  O              15.999       0.00001       0.00000       N
  END
```

REEDM does not utilize the launch vehicle trajectory directly; instead a power law fit to the height of the vehicle above ground as a function of time is derived from the trajectory data. The fit achieved with the derived power law time-height coefficients is demonstrated in Figure 3-1

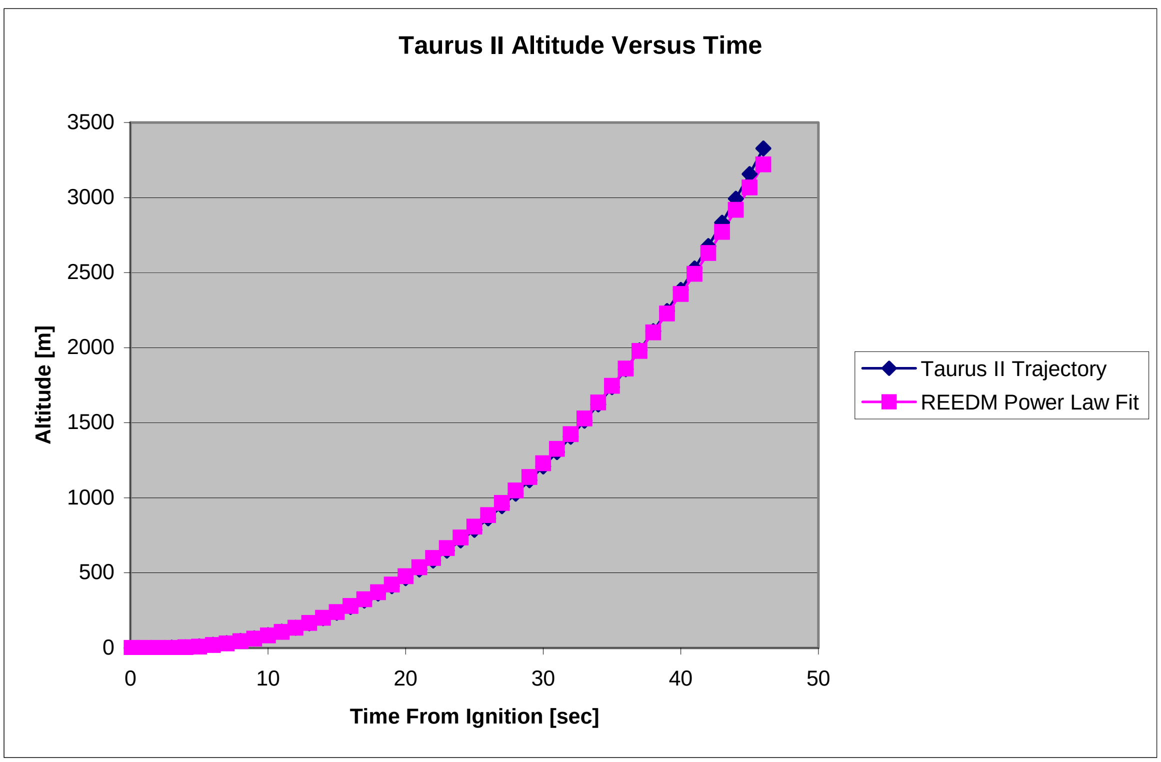

Figure 3-1. Plot of Vendor Taurus II Nominal Trajectory Compared with ACTA Derived Power Law Fit Used in REEDM.

REEDM allows for several chemical additions that may be included in the propellant exhaust of the normal launch ground cloud and the normal launch contrail cloud. In addition to specifying the nominal burn rates of the RP-1 fuel and the LOX oxidizer, the user may optionally consider adding deluge or sound suppression water and entrained ambient air. For these two items the REEDM database serves only as a source of documentation for the assumptions applied in deriving the chemical compositions of the exhaust specified in section #05.02 of the database. It is noted here that "air entrainment" as specified in this section represents the user assumption about the amount of air, if any, added as a ***reactant*** in the propellant combustion calculations. This "air entrainment" definition is not to be confused with the "air entrainment" process that takes place during the cloud rise calculations. REEDM assumes that all chemical combustion reactions are completed before the cloud rise process takes place and REEDM therefore does not attempt to recompute chemical composition and additional heat release during the cloud rise computations.

The REEDM database provides the chemical composition of the normal ground and contrail clouds. A mass fraction is assigned to each constituent and the total exhaust mass in the source cloud is multiplied by this fraction to determine the total mass of each chemical in the exhaust cloud. The molecular weight of each species is used to convert the concentration from mass per unit volume [e.g.mg/m^3] to parts per million. For this study ACTA computed the chemical composition of the Taurus II stage 1 RP-1/LOX exhaust using the NASA Lewis chemical equilibrium combustion model. The ACTA version of the NASA combustion model was modified slightly to output thermodynamic properties of the exhaust mixture that were needed to initialize the REEDM cloud rise equations. ACTA's combustion results for the Taurus II first stage agreed within 2% for the major constituents (CO, CO_2, H_2O) compared with similar data provided by Orbital Sciences 0 as shown in Table 3-1. ACTA ran the NASA combustion model in "rocket" analysis mode using an oxidizer to fuel ratio of 2.7 and a combustion chamber pressure of 2194 PSIA. The Orbital analysis appears to have been conducted with a newer version of the NASA equilibrium combustion model and was executed with a slightly different nozzle to throat area ratio than the ACTA model. The supporting thermodynamic databases between the two versions of the combustion models may also differ slightly. ACTA considers the small chemical composition differences to have insignificant effect on the analysis results and conclusions of this study.

Table 3-1. Comparison of ACTA and Orbital Taurus II Stage-1 Combustion Model Nozzle Exit Results.

Chemical	ACTA Mole Fraction	Orbital Mole Fraction	Ratio ACTA/Orbital
CO_2	0.26632	0.27071	0.984
CO	0.23932	0.23532	1.017
H_2O	0.41938	0.41627	1.007
H_2	0.07231	0.07650	0.945
OH	0.00118	0.00048	2.458
H	0.00144	0.00072	2.000
O_2	0.00004	0.00001	4.000
O	0.00002	0.00000	--

Both ACTA and Orbital ran combustion for only RP-1 and LOX and the chemical compositions listed in Table 3-1 do not consider the shift in chemical equilibrium that takes place if ambient air or water are added to the nozzle exit exhaust mixture.

3.2 Static Test Firing Vehicle Data

The REEDM database also includes a data section used to define the parameters that characterize a static test firing scenario. The data developed for the Taurus II stage-1 static test firing is listed as follows:

```
#05.20 TEST FIRING ENGINE DATA:
   SOLID FUEL MASS                          (LBM) = 123552.,
   SOLID FUEL BURN RATE                   (LBM/S) =   2376.,
   AIR ENTRAINMENT RATE IN CLOUD          (LBM/S) =       0,
   TOTAL DELUGE WATER ENTRAINED IN CLOUD    (LBM) =       0,
   CLOUD INITIAL AVERAGE TEMPERATURE          (F) =    3487,
   CLOUD INITIAL HEAT CONTENT           (BTU/LBM) =    3475,
   INITIAL VERTICAL VELOCITY OF CLOUD      (FT/S) =     0.0,
   INITIAL RADIUS OF CLOUD                   (FT) =   151.1,
   INITIAL HEIGHT OF CLOUD                   (FT) =     0.0,
   INITIAL X DISPLACEMENT OF CLOUD FROM STAND (FT) =     0.0,
   INITIAL Y DISPLACEMENT OF CLOUD FROM STAND (FT) =     0.0,
#05.21 TEST FIRING PLUME CHEMISTRY  DATA:
 CHEMICAL NAME     MOL. WT.   MASS FRAC. GAS   MASS FRAC. COND  HAZARDOUS
   CO2              44.011        0.44824          0.00000          Y
   CO               28.011        0.25637          0.00000          Y
   H2O              18.015        0.28893          0.00000          N
   H2                2.016        0.00557          0.00000          N
   OH               17.007        0.00077          0.00000          N
   H                 1.008        0.00006          0.00000          N
   O2               31.999        0.00005          0.00000          N
   O                15.999        0.00001          0.00000          N
   END
```

The REEDM static test firing scenario was originally developed for burns of solid propellant motors and the nomenclature used in the database is outdated and somewhat misleading. In the case of the Taurus II first stage test firing the line items identified as "solid fuel mass" and "solid fuel burn rate" are set to represent the total quantity of RP-1 + LOX and the average burn rate of the RP-1 + LOX mixture consumed during a 52 second static burn. The chemical composition of the static test firing exhaust is set the same as the normal launch ground cloud. As with the normal launch scenario, the effects of plume afterburning and deluge water injection are ignored.

3.3 Conservative Assumptions Applied In Data Development

The REEDM atmospheric dispersion model has been used operationally by the Air Force to make range safety launch decisions since 1989. During that time vehicle databases have been developed for many vehicles (e.g. Space Shuttle, Titan II, Titan III, Titan IV, Delta II, Delta III, Delta IV, Atlas II, Atlas III, Atlas V, Taurus, TaurusXL, Taurus Lite, Minotaur, Peacekeeper, Minuteman II, Minuteman III, Athena, Lance, Scud, ATK-ALV-1). As noted at the beginning of this section, some vehicle data is easily obtained and verified, such as the stage propellant types, quantities and burn rates. Other model input parameters required by REEDM are based on derived values obtained from mathematical and physical models, empirical measurement data or engineering judgment from the vehicle designer or range safety experts.

An example of a derived value is the selection of how much pad deluge water to include with the rocket engine exhaust when defining the normal launch cloud heat content, mass and chemical composition. A typical pad deluge system is comprised of a series of pressure fed sprayers and sprinkers that wet the launch pad, the launch service tower and the flame duct. The deluge system is typically turned on several seconds before the rocket motors are ignited and continues until the rocket has ascended above the launch tower and the plume no longer impinges on the ground. As the vehicle ascends, the rocket plume interaction with the pad structures is time varying, such that the gas flow velocity ranges from supersonic to subsonic and involves multiple shock fronts, reflected shocks, deflected flow from the pad surface, partial flow ducting through the flame trench and plume temperatures that range from 300 to 3000 K. A simple energy balance between the amount of heat available in the plume and the amount of water released in the deluge system may suggest that there is ample energy to vaporize all of the deluge water, but actual observation of launches indicates that residual deluge water is often collected in a concrete containment basin designed to collect residual deluge water. Likewise the initial ignition impulse often blows standing water out of the flame trench or away from the pad and depositing it as droplets before they can be fully mixed with the combustion gases and vaporized. Some parts of the launch plume during vehicle liftoff may become saturated with water vapor and other portions may remain relatively “dry”. Thus the task of selecting a specific deluge water inclusion amount for the REEDM database and setting the associated chemical and thermodynamic data for the exhaust products is challenging and typically not estimated by the launch agency or vehicle developer. This type of flow problem is extremely complex and would require advanced computational fluid dynamics analysis that is extremely costly and also constrained by modeling assumptions. Consequently, these types of detailed analyses are rarely performed or conducted only for limited specific design purposes.

Other examples of highly uncertain processes are the mixing of propellants from ruptured tanks in a vehicle explosion, and the fragmentation of a solid rocket motor propellant grain in the event of a case rupture. These latter events are related to vehicle failures that are not considered in this study, however, they illustrate the problem routinely faced by the launch community when attempting to set up REEDM database entries to model these scenarios. Historically the range safety community has taken a conservative approach in setting these uncertain database entries. The vast majority of vehicles characterized in the REEDM database ignore deluge water contributions (a notable exception being Shuttle). One reason for ignoring the deluge water effect is that it is known that water vapor and water droplets scrub hydrogen chloride (a common solid propellant toxic exhaust product) from the launch plume but the degree of the effect is difficult to quantify and verify, therefore ignoring this removal mechanism favors maximizing the downwind ground level concentrations of HCl at receptor sites of concern that must be protected.

The same philosophy of erring in favor of overestimating rather than underestimating potential emission hazards has been applied in this study of the Taurus II carbon monoxide emissions. There are two main factors to which conservative assumptions have been applied in this study; 1) ambient air entrainment and its effect on plume afterburning chemistry, and 2), deluge water injection into the plume. Both of these factors are discussed in further detail in the following paragraphs with an explanation for why it is believed that the REEDM modeling assumptions applied in this study are in fact conservative.

It is recognized that the Taurus II, like most rocket engines, is designed to run somewhat fuel rich for efficiency reasons and that the exhaust products will contain compounds (mainly CO and OH) that are not fully oxidized. Entrainment of ambient air into the superheated gases exiting from the rocket nozzle will allow for further oxidation in the plume, a process referred to as plume afterburning. The rate of air entrainment into the plume and the amount of additional oxidation that occurs in the plume downstream from the nozzle exit plane requires sophisticated computation fluid dynamic (CFD) solutions of the plume flow as it decelerates through multiple shock front to subsonic velocity that are beyond the design capabilities and run time requirements of REEDM. In this study ACTA has ignored the effect of air entrainment on the combustion products and heat content of the normal launch ground cloud and contrail cloud emissions. Ignoring air entrainment and after burning is assumed to be conservative for this study in that the ground level CO concentration predictions will err on the side of overestimating rather than underestimating the concentration for the following two reasons:

1. Ignoring ambient air entrainment in the combustion calculations will favor production of CO rather than CO_2 and CO is the more toxic species.

2. Ignoring ambient air afterburning reduces the total amount of heat released by the combustion process, which in turn leads to a lower stabilized cloud height prediction. Ground level concentrations of cloud chemicals vary approximately with the inverse cube of the stabilization height (e.g. doubling the cloud stabilization height reduces the ground concentrations by about a factor of 8, other factors being constant). Lower stabilization height therefore favors higher ground level CO predictions.

A deluge water system is planned for the Taurus II launch pad and serves to cool pad structures exposed to rocket engine exhaust as well as to suppress acoustic vibrations during motor ignition. An objective of the deluge water system design is to inject water into the plume just downstream of the nozzle exit plane at a rate of 2 lbm of water for every lbm of rocket propellant exhaust. Water is expected to chemically react with the high temperature rocket engine exhaust gases, which are fuel rich. In this situation water acts as an oxidizer and gives up oxygen to convert CO to CO_2 in the plume while simultaneously releasing hydrogen gas. The reaction between high temperature CO and H_2O is referred to as the “water-gas shift” reaction. ACTA evaluated the effect of 2:1 water to rocket exhaust mixing on the plume chemistry immediately downstream of the nozzle exit plane by running the NASA Lewis chemical equilibrium combustion model 0, 0 using the RP-1/LOX nozzle exit products as high temperature reactants at 2193 K mixed with liquid water at 298 K. The input reactant information entered into the combustion model is listed below:

NASA Lewis Combustion Model Input Reactants for RP-1/LOX Exhaust Products and Deluge Water Mixture.

```
THERMO
TRAN
REACTANTS
C 1.     O 2.0                        63.111  -69368.  G 2193.  F
C 1.     O 1.0                        36.096  -11178.  G 2193.  F
H 2.                                   0.784   14240.  G 2193.  F
H 1.                                   0.008   61472.  G 2193.  F
H 2.     O 1.0                        87.345  -68267.  L  298.  O
H 2.     O 1.0                        12.619  -37989.  G 2193.  O
O 2.                                   0.002   15877.  G 2193.  O
O 1.     H 1.0                         9.631   23759.  G 2193.  O
```

```
NAMELISTS
 &inpt2 kase=1,hp=t,p=1.000,of=t,mix=3.2239,siunit=t &end
```

The predicted combustion products and thermodynamic state properties for the exhaust plume + water mixture are listed below. Post combustion products are highlighted. Note that the plume is cooled from 2193 K to 856 K, but remains unsaturated. The predicted amount of CO in the exhaust has dropped from 25.6% to 0.3%, a reduction factor of approximately 100. CO_2 concentration is predicted to decrease from 44.8% to 27.9%. The total amount of CO_2 produced has actually increased but the percentage relative to the total exhaust mixture mass has decreased.

NASA Lewis Combustion Model Output Products for RP-1/LOX Exhaust and Deluge Water Mixture.

```
0                  O/F=   3.2239     PERCENT FUEL=   23.6748     EQUIVALENCE RATIO= 1.0383     PHI=
2.0181
0THERMODYNAMIC PROPERTIES

 P, MPA            0.10132
 T, DEG K           856.32
 RHO, KG/CU M    2.9654-1
 H, KJ/KG         -11095.9
 U, KJ/KG         -11437.6
 G, KJ/KG         -20674.8
 S, KJ/(KG)(K)     11.1861

 M, MOL WT          20.837
 (DLV/DLP)T       -1.00000
 (DLV/DLT)P         1.0000
 CP, KJ/(KG)(K)     1.9758
 GAMMA (S)          1.2531
 SON VEL,M/SEC       654.3
   trace =    0.000000000000000E+000
   npt   =             1
 total product molecular wt. (including condensed sp) = 20.837

0MOLE FRACTIONS

   oxidizer mass fraction =    0.7632520
   fuel mass fraction     =    0.2367480
  C O           -69368.0    44.010  F    0.6311
  C O           -11178.0    28.010  F    0.3610
  H              14240.0     2.016  F    0.0078
  H              61472.0     1.008  F    0.0001
  H O           -68267.0    18.015  O    0.7970
  H O           -37989.0    18.015  O    0.1151
  O              15877.0    31.999  O    0.0000
  O H            23759.0    17.007  O    0.0879

   oxfl =    3.22390007972717
   temperature =    856.317902340247
   Total reactant enthalpy [cal/g] =    -2651.987

   INJECTOR CONDITIONS
```

chemical	mole frac	mole wt	wt kg	wt frac	hval cal/gmole	hf298 cal/gmole	heat cal	heat@stag cal	hstag cal/gmole
H2O	0.82599	18.015	14.88037	0.71412	-52929.2	-57754.7	3985.8	3985.8	-52929.2
CO2	0.13216	44.010	5.81651	0.27914	-87837.4	-93983.8	812.3	812.3	-87837.4
H2	0.03969	2.016	0.08002	0.00384	3910.7	0.6	155.2	155.2	3910.7
CO	0.00215	28.010	0.06027	0.00289	-22342.6	-26398.0	8.7	8.7	-22342.6

```
  total kg products (per kgmole) =     20.83716
```

```
total heat of form. of prod. [cal/gmole] =   -60182.82
enthalpy of prod. at plume T [cal/gmole]=   -55220.72
heat content of prod. @ plume T & V [cal/gmole] =    4962.093
heat content of prod. @ plume T & V [cal/g] =    238.1358
total weight fractions of products =   0.9999962
total mole fractions of products =   0.9999994
gas velocity [m/sec] =   0.0000000E+00
stagnation enthalpy of prod. [cal/gmole]=   -55220.72
heat content of prod. @ stag T & V = 0 [cal/gmole] =    4962.093
heat content of prod. @ stag T & V = 0  [cal/g] =    238.1358
total heat of form. of reac. [cal/g] =   -2651.987
heat of combustion [cal/g] =    236.2465
```

The addition of deluge water has another effect in that it may reduce the net heat content of the cloud in proportion to the amount of liquid deluge water that is converted to gaseous phase and does not chemically react with other plume constituents. The amount of liquid water that is vaporized and then does not re-condense during the cloud rise phase reduces the cloud buoyancy. The effects of deluge water on the plume chemistry and plume rise where ignored in this study, in part because the normal launch plume has a time varying interaction with the deluge system and transitions from a high water injection condition to an essentially dry plume. Ignoring deluge or sound suppression water injection into the plume is expected to be conservative in that it should lead to model predictions that overestimate the downwind ground level CO concentrations. The reduction of in-cloud CO is expected to far outweigh the reduction in cloud stabilization height due to loss of thermal buoyancy.

4. ANALYSIS OF EMISSION SCENARIOS

The REEDM Taurus II database was used in conjunction with a large set of archived WFF weather balloon soundings to predict downwind concentrations of carbon monoxide and to achieve some statistical perspective of the potential toxic hazard corridors associated with normal launch and static test firing scenarios.

4.1 Meteorological Data Preparation

Gaseous dispersion of rocket exhaust clouds is extremely dependent upon the meteorological conditions at the time the source cloud is generated. The presence or absence of temperature inversions, the temperature lapse rate, wind speed and direction, wind shears and atmospheric turbulence are important factors that influence the cloud rise and rate of dispersion of the source cloud. Meteorological conditions that are adverse from a toxic chemical dispersion perspective are light winds with little wind speed or wind direction variation over the first several thousand feet of the atmosphere coupled with a capping temperature inversion just above the top of the stabilized source cloud. An additional adverse factor is suppression of atmospheric turbulence, as occurs at night or under cloudy or marine stratus and fog conditions.

ACTA acquired and ran REEDM analyses for 6432 meteorological cases based on actual weather balloon measurements made at Wallops Flight Facility between 2000 and 2008. The raw weather balloon data was not in a format usable by REEDM and needed to be preprocessed to reduce the number of measurement levels from several thousand to approximately one hundred, to quality control check the raw data, and to output the data in REEDM compatible format. A computer program written by ACTA and delivered to WFF for operational use in 2007 was used to perform the raw data file conversions. A critical part of the conversion process is to test for, and capture, inflection points where temperature, wind speed, wind direction or relative humidity reach minimum or maximum values and change slope as a function of altitude. An example of the weather profile testing algorithm capabilities is illustrated in Figure 4-1, which is contrived test data with positive, negative and infinite slopes and multiple inflection points. The resulting converted files were sorted into daytime and nighttime sets for each month of the year. Data was classified as “daytime” if the balloon release time was between 0600 and 1900 Eastern Standard Time.

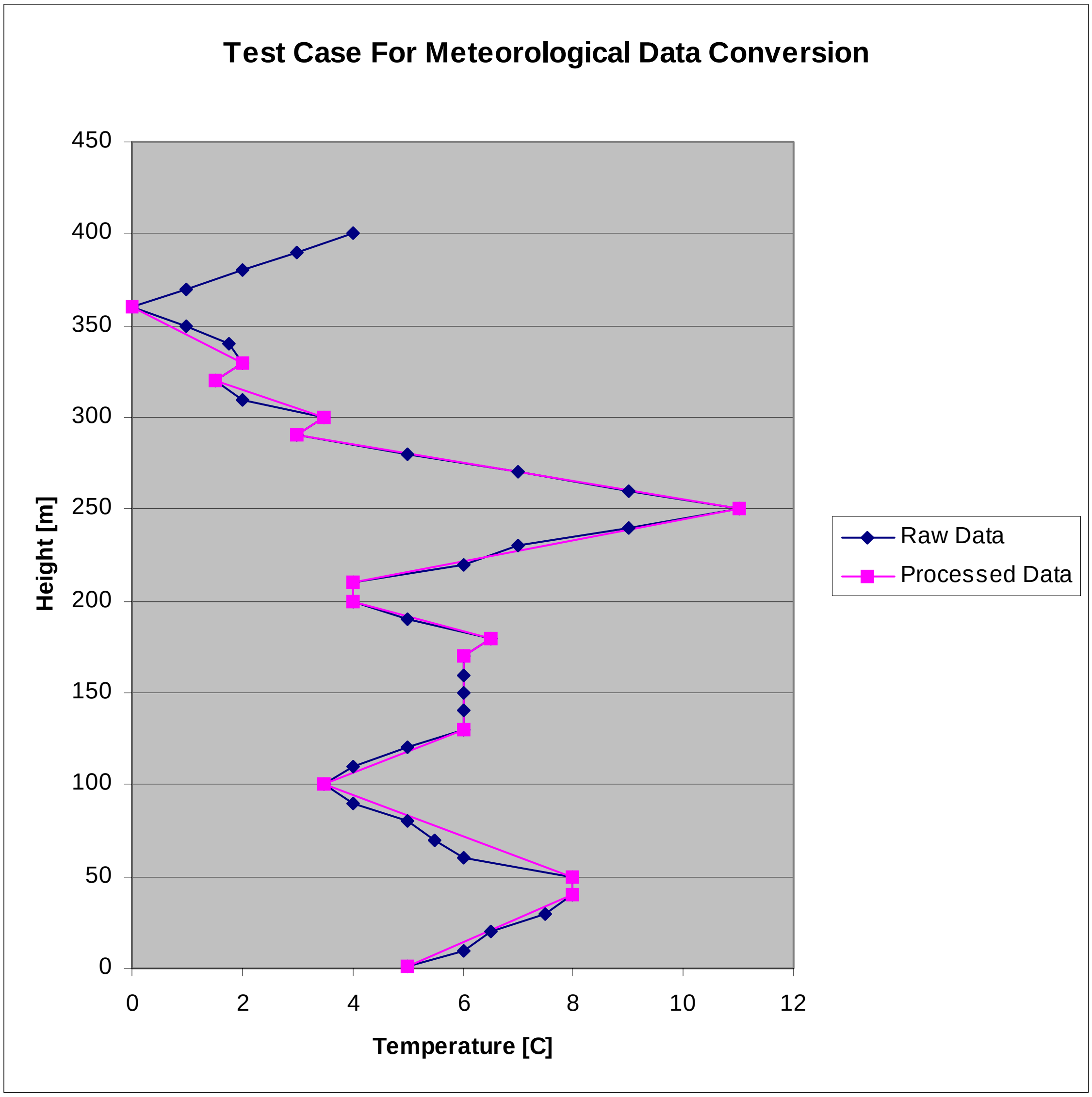

Figure 4-1. Illustration of Testing a Raw Data Profile to Capture Slope Inflection Points that Define Minimum and Maximum Values and Measure Inversions and Shear Effects.

4.2 REEDM Far Field Results For Taurus II Normal Launch Scenario

ACTA executed REEDM in batch processing mode to cycle through all archived meteorological cases and to extract key information to a summary table. Typically REEDM generates an output file for a single weather case that consists of 10 to 20 pages of information on the run setup, intermediate calculated value and tables of concentration versus downwind distance. When processing thousands of cases, saving the standard REEDM output file for each run results in an overwhelming amount of output data. ACTA developed a special batch version of REEDM for the Air Force that has been used over the years to execute thousands of scenarios and condense the REEDM output for all runs into a summary table containing the following critical analysis parameters:

1. Chemical being tracked in REEDM analysis.
2. Concentration threshold used to calculate concentration isopleth beginning and end distances.
3. Meteorological input file name.
4. Zulu time of balloon release.
5. REEDM computed mixing boundary depth.
6. REEDM predicted cloud stabilization height.
7. REEDM predicted average wind speed used to transport exhaust cloud.
8. REEDM predicted average wind direction used to transport exhaust cloud.
9. REEDM predicted maximum ground level concentration.
10. REEDM predicted distance from exhaust cloud source to location of maximum concentration.
11. REEDM predicted bearing from exhaust cloud source to location of maximum concentration.
12. REEDM predicted nearest distance from exhaust cloud source to the location where the ground concentration centerline first exceeds the user defined concentration threshold.
13. REEDM predicted farthest distance from exhaust cloud source to the location where the ground concentration centerline last exceeds the user defined concentration threshold.
14. REEDM predicted bearing from exhaust cloud source to location where the ground concentration centerline last exceeds the user defined concentration threshold.
15. REEDM derived average wind speed shear in the lower planetary boundary layer.
16. REEDM derived average wind direction shear in the lower planetary boundary layer.

17. REEDM derived average horizontal (azimuthal) turbulence intensity in the lower planetary boundary layer.

18. REEDM derived average vertical (elevation) turbulence intensity in the lower planetary boundary layer.

19. REEDM derived average wind speed shear in the region above the planetary boundary layer.

20. REEDM derived average wind direction shear in the region above the planetary boundary layer.

21. REEDM derived average horizontal (azimuthal) turbulence intensity in the region above the planetary boundary layer.

22. REEDM derived average vertical (elevation) turbulence intensity in the region above the planetary boundary layer.

The above list of parameters is provided for REEDM predictions of both peak instantaneous concentration and time weighted average (TWA) concentration. In the runs performed for this study a 1-hour averaging time was used to compute time weighted average concentrations. A fairly short averaging time is appropriate for rocket exhaust cloud exposures because the source cloud typically passes over a receptor with a time scale of tens of minutes rather than hours. The REEDM summary tables from the monthly batch runs were further condensed to identify the meteorological case that produced the highest peak concentration and record the range and bearing from the source location (WFF Taurus II launch Pad-0A). Table 4-1 presents the maximum far field CO peak instantaneous concentration predicted by REEDM for the hypothetical daytime launches of a Taurus II with subsequent dispersion of the normal launch ground and contrail clouds. The far field exposure is REEDM's prediction for concentrations at ground level downwind of the stabilized exhaust cloud. Far field peak CO concentrations ranged from 3 to 8 ppm with the maximum concentration predicted to occur from 5000 to 16000 meters downwind from the launch site. These values represent the maximum concentrations predicted over a sample set of 4704 WFF balloon soundings. Table 4-2 lists the maximum predicted far field 1-hour TWA concentrations of CO for daytime normal launch scenarios. The maximum TWA concentrations are all predicted to be less than 1 ppm. Table 4-3 and Table 4-4 show the REEDM predicted maximum peak and maximum TWA CO far field concentrations for 1728 nighttime cases for Taurus II normal launch scenarios. As with the daytime cases, the peak instantaneous CO concentrations are less than 10 ppm and the peak TWA CO concentrations are less than 1 ppm.

Table 4-1: Taurus II Normal Launch CO Concentration Summary – Daytime Meteorology.

Month	Number of Weather Cases	Peak CO Concentration [ppm]	Distance to Peak CO Concentration [m]	Bearing to Peak CO Concentration [deg]
January	344	4.7	8000	73
February	364	4.9	8000	158
March	397	5.1	7000	285
April	383	6.1	8000	249
May	398	7.9	7000	245
June	392	4.3	6000	258
July	416	5.4	5000	285
August	408	6.0	8000	226
September	413	4.7	9000	22
October	435	2.9	16000	240
November	382	4.0	11000	205
December	372	6.4	6000	83

Table 4-2. Taurus II Normal Launch CO TWA Concentration Summary – Daytime Meteorology.

Month	Number of Weather Cases	Peak CO Concentration [ppm]	Distance to Peak CO Concentration [m]	Bearing to Peak CO Concentration [deg]
January	344	0.22	7000	259
February	364	0.17	3000	23
March	397	0.19	11000	315
April	383	0.23	7000	228
May	398	0.34	11000	300
June	392	0.32	4000	51
July	416	0.32	7000	274
August	408	0.21	6000	133
September	413	0.18	7000	305
October	435	0.24	13000	108
November	382	0.20	28000	120
December	372	0.17	15000	127

Table 4-3: Taurus II Normal Launch CO Concentration Summary – Nighttime Meteorology.

Month	Number of Weather Cases	Peak CO Concentration [ppm]	Distance to Peak CO Concentration [m]	Bearing to Peak CO Concentration [deg]
January	93	5.5	8000	74
February	157	4.0	10000	74
March	162	3.7	10000	176
April	156	6.3	9000	226
May	158	6.2	11000	242
June	152	4.4	7000	114
July	153	4.4	8000	113
August	162	3.4	10000	82
September	163	2.7	9000	356
October	119	2.7	18000	259
November	125	3.8	9000	91
December	128	6.0	7000	149

Table 4-4. Taurus II Normal Launch CO TWA Concentration Summary – Nighttime Meteorology.

Month	Number of Weather Cases	Peak CO Concentration [ppm]	Distance to Peak CO Concentration [m]	Bearing to Peak CO Concentration [deg]
January	93	0.08	9000	74
February	157	.09	24000	77
March	162	0.10	13000	230
April	156	0.60	7000	46
May	158	0.17	16000	120
June	152	0.24	7000	210
July	153	0.15	14000	34
August	162	0.20	12000	223
September	163	0.16	12000	226
October	119	0.08	28000	59
November	125	0.20	7000	202
December	128	0.17	21000	146

The REEDM predicted CO concentrations for all daytime meteorological cases processed in the 8-year sample set was aggregated into bins to evaluate the peak far field concentration probability. This information is provided in Table 4-5 and it is noted that approximately 81% of all daytime meteorological cases resulted in REEDM maximum peak instantaneous ground level CO concentrations of less than 1 ppm.

Table 4-5. REEDM Predicted Maximum Far Field Ground Level Carbon Monoxide Concentrations For Daytime Taurus II Normal Launch Scenarios.

Concentration Bin	Count	Probability
0 - 1	3805	0.809
1 - 2	644	0.137
2 - 3	174	0.037
3 - 4	54	0.011
4 - 5	14	0.003
5 - 6	9	0.002
6 - 7	3	0.001
7 - 8	1	0.0002
8 - 9	0	0.0000
9 - 10	0	0.0000

The REEDM predicted CO 1-hour time weighted average concentrations for all daytime meteorological cases processed in the 8-year sample set was aggregated into bins to evaluate the peak far field TWA concentration probability. This information is provided in Table 4-6 and it is noted that approximately 88% of all daytime meteorological cases resulted in REEDM maximum 1-hour TWA ground level CO concentrations of less than 0.04 ppm. The fact that the TWA concentration is much less than the peak instantaneous concentration is consistent with the short cloud passage time.

The REEDM predicted cloud transport directions were also aggregated into bins representing 45-degree arc corridors around the compass (i.e. N, NE, E, SE, S, SW, W, NW). Table 4-7 indicates the predicted Taurus II normal launch plume direction probability of occurrence observed across the 4704 daytime balloon soundings. It is noted that for the daytime launch scenarios transport of the exhaust plume to the East is favored. The transport direction reflects the average airflow over a depth of approximately 1000 meters, hence the windrose observed for elevated rocket exhaust clouds may differ significantly from a windrose derived from a surface wind tower.

Table 4-6. REEDM Predicted Maximum Far Field Ground Level Carbon Monoxide TWA Concentrations For Daytime Taurus II Normal Launch Scenarios.

1-Hour TWA Concentration Bin	Count	Probability
0.00 – 0.02	1933	0.411
0.02 – 0.04	1464	0.311
0.04 - 0.06	735	0.156
0.06 - 0.08	285	0.061
0.08 - 0.10	126	0.027
0.10 - 0.12	66	0.014
0.12 - 0.14	35	0.007
0.14 - 0.16	18	0.004
0.16 - 0.18	17	0.004
0.18 – 0.20	10	0.002
0.20 – 0.22	3	0.001
0.22 – 0.24	3	0.001
0.24 – 0.26	2	0.0004
0.26 – 0.28	2	0.0004
0.28 – 0.30	2	0.0004
0.30 – 0.32	0	0.0000
0.32 – 0.34	2	0.0004
0.34 – 0.36	1	0.0002
0.36 – 0.38	0	0.0000
0.38 -0.40	0	0.0000

Table 4-7. REEDM Predicted Exhaust Cloud Transport Directions For Daytime Taurus II Normal Launch Scenarios.

Plume Transport Direction Bin	Count	Probability
337.5 – 22.5 (N)	363	0.077
22.5 – 67.5 (NE)	830	0.176
67.5 – 112.5 (E)	801	0.170
112.5 – 157.5 (SE)	976	0.207
157.5 – 202.5 (S)	515	0.109
202.5 – 247.5 (SW)	453	0.096
247.5 – 292.5 (W)	326	0.069
292.5 – 337.5 (NW)	440	0.094

Similar summary tables for the 1728 nighttime Taurus II normal launch simulations were compiled. Table 4-8 shows that the peak CO instantaneous concentration predictions for nighttime conditions continues with a high probability that the maximum far field concentration will be less than 1 ppm.

Table 4-8. REEDM Predicted Maximum Far Field Ground Level Carbon Monoxide Concentrations For Nighttime Taurus II Normal Launch Scenarios.

Concentration Bin	Count	Probability
0 - 1	1390	0.804
1 - 2	237	0.137
2 - 3	67	0.039
3 - 4	23	0.013
4 - 5	7	0.004
5 - 6	2	0.0012
6 - 7	2	0.0012
7 - 8	0	0.0000
8 - 9	0	0.0000
9 - 10	0	0.0000

The REEDM predicted CO 1-hour time weighted average concentrations for all nighttime meteorological cases is provided in Table 4-9 and it is noted that approximately 73% of all nighttime meteorological cases resulted in REEDM maximum 1-hour TWA ground level CO concentrations of less than 0.04 ppm.

Table 4-10 indicates the predicted Taurus II normal launch plume direction probability of occurrence observed across the 1728 nighttime balloon soundings. It is noted that for nighttime launch scenarios transport of the exhaust plume to the East is still favored as it was during the daytime.

Table 4-9. REEDM Predicted Maximum Far Field Ground Level Carbon Monoxide TWA Concentrations For Nighttime Taurus II Normal Launch Scenarios.

1-Hour TWA Concentration Bin	Count	Probability
0.00 – 0.02	817	0.473
0.02 – 0.04	449	0.260
0.04 - 0.06	264	0.153
0.06 - 0.08	114	0.066
0.08 - 0.10	52	0.030
0.10 - 0.12	12	0.007
0.12 - 0.14	6	0.0035
0.14 - 0.16	4	0.0023
0.16 - 0.18	5	0.0029
0.18 – 0.20	0	0.0000
0.20 – 0.22	3	0.0017
0.22 – 0.24	0	0.0000
0.24 – 0.26	0	0.0000
0.26 – 0.28	0	0.0000
0.28 – 0.30	0	0.0000
0.30 – 0.32	0	0.0000
0.32 – 0.34	0	0.0000
0.34 – 0.36	0	0.0000
0.36 – 0.38	0	0.0000
0.38 -0.40	0	0.0000

Table 4-10. REEDM Predicted Exhaust Cloud Transport Directions For Nighttime Taurus II Normal Launch Scenarios.

Plume Transport Direction Bin	Count	Probability
337.5 – 22.5 (N)	61	0.035
22.5 – 67.5 (NE)	315	0.182
67.5 – 112.5 (E)	296	0.171
112.5 – 157.5 (SE)	369	0.214
157.5 – 202.5 (S)	231	0.134
202.5 – 247.5 (SW)	215	0.124
247.5 – 292.5 (W)	106	0.061
292.5 – 337.5 (NW)	135	0.078

4.3 REEDM Far Field Results For The Taurus II Static Test Firing Scenario

REEDM was executed in batch mode using the same archived WFF meteorological soundings to evaluate the formation, transport and ground level concentration of CO from Taurus II static test firings on the launch stand. Table 4-11 presents the maximum peak instantaneous CO concentration predicted for the static test firing. It is noted that in general the static test firing is predicted to produce higher ground level CO concentrations than the normal launch scenario.

Table 4-11: Taurus II Static Test Firing CO Concentration Summary – Daytime Meteorology.

Month	Number of Weather Cases	Peak CO Concentration [ppm]	Distance to Peak CO Concentration [m]	Bearing to Peak CO Concentration [deg]
January	344	10.8	6000	53
February	364	15.5	6000	31
March	397	18.9	6000	34
April	383	13.5	6000	33
May	398	11.6	7000	16
June	392	6.1	8000	21
July	416	5.2	7000	75
August	408	5.2	11000	25
September	413	9.2	8000	249
October	435	5.9	6000	58
November	382	11.8	6000	92
December	372	13.6	8000	37

Table 4-12 lists the predicted daytime CO TWA concentrations for the Taurus II static test firing scenarios. The TWA concentrations are somewhat higher than the corresponding values predicted for the normal launch scenario, but the overall expectation is that the 1-hour TWA CO concentrations will be less than 1 ppm. Table 4-13 and Table 4-14 show the maximum predicted CO instantaneous and 1-hour TWA concentrations for the nighttime static test firing conditions.

Table 4-12. Taurus II Static Test Firing CO TWA Concentration Summary – Daytime Meteorology.

Month	Number of Weather Cases	Peak CO Concentration [ppm]	Distance to Peak CO Concentration [m]	Bearing to Peak CO Concentration [deg]
January	344	0.20	7000	53
February	364	0.27	8000	70
March	397	0.26	5000	46
April	383	0.23	9000	20
May	398	0.25	11000	251
June	392	0.16	5000	61
July	416	0.18	4000	181
August	408	0.14	14000	136
September	413	0.15	7000	241
October	435	0.17	14000	221
November	382	0.23	6000	92
December	372	0.25	9000	37

Table 4-13: Taurus II Static Test Firing CO Ceiling Concentration Summary – Nighttime Meteorology.

Month	Number of Weather Cases	Peak CO Concentration [ppm]	Distance to Peak CO Concentration [m]	Bearing to Peak CO Concentration [deg]
January	93	12.3	6000	100
February	157	8.7	7000	8
March	162	11.4	6000	40
April	156	13.7	5000	58
May	158	7.2	6000	80
June	152	5.9	6000	113
July	153	4.2	8000	83
August	162	4.7	9000	82
September	163	4.6	13000	72
October	119	6.1	8000	59
November	125	6.9	8000	92
December	128	13.6	8000	37

Table 4-14. Taurus II Static Test Firing CO TWA Concentration Summary – Nighttime Meteorology.

Month	Number of Weather Cases	Peak CO Concentration [ppm]	Distance to Peak CO Concentration [m]	Bearing to Peak CO Concentration [deg]
January	93	0.22	7000	100
February	157	0.24	16000	42
March	162	0.21	11000	29
April	156	0.28	7000	58
May	158	0.23	13000	100
June	152	0.15	7000	113
July	153	0.11	18000	83
August	162	0.12	10000	79
September	163	0.30	12000	226
October	119	0.13	12000	152
November	125	0.18	11000	66
December	128	0.25	9000	37

Histograms of REEDM predicted CO concentrations for Taurus II static test firings for all daytime meteorological cases were generated in a similar fashion to the normal launch scenario. Table 4-15 presents the maximum predicted CO concentrations and it is noted that approximately 76% of all daytime meteorological cases resulted in REEDM maximum peak instantaneous ground level CO concentrations of less than 1 ppm. The static test firing scenarios exhibited a trend toward somewhat higher concentrations than predicted for the normal launch.

Table 4-15. REEDM Predicted Maximum Far Field Ground Level Carbon Monoxide Concentrations For Daytime Taurus II Static Test Firing Scenarios.

Concentration Bin	Count	Probability
0 - 1	3568	0.759
1 - 2	632	0.134
2 - 3	195	0.041
3 - 4	125	0.027
4 - 5	51	0.011
5 - 6	48	0.010
6 - 7	21	0.004
7 - 8	18	0.004
8 - 9	14	0.003
9 +	12	0.003

Table 4-16 presents the REEDM predicted CO 1-hour time weighted average concentrations for all daytime meteorological cases processed for the Taurus II static test firing scenario. It is noted that approximately 60% of all daytime meteorological cases resulted in REEDM maximum 1-hour TWA ground level CO concentrations of less than 0.04 ppm.

The REEDM predicted cloud transport directions were also aggregated into bins for the static test firing scenario. Table 4-17 indicates the predicted Taurus II static test firing plume direction probability of occurrence observed across the 4704 daytime balloon soundings. It is noted that for the daytime launch scenarios transport of the exhaust plume to the East is favored.

Table 4-16. REEDM Predicted Maximum Far Field Ground Level Carbon Monoxide TWA Concentrations For Daytime Taurus II Static Test Firing Scenarios.

1-Hour TWA Concentration Bin	Count	Probability
0.00 – 0.02	1468	0.312
0.02 – 0.04	1372	0.292
0.04 - 0.06	863	0.183
0.06 - 0.08	446	0.095
0.08 - 0.10	230	0.049
0.10 - 0.12	138	0.029
0.12 - 0.14	74	0.016
0.14 - 0.16	40	0.009
0.16 - 0.18	29	0.006
0.18 – 0.20	17	0.004
0.20 – 0.22	15	0.003
0.22 – 0.24	6	0.0012
0.24 – 0.26	3	0.0006
0.26 – 0.28	2	0.0004
0.28 – 0.30	0	0.0000
0.30 – 0.32	0	0.0000
0.32 – 0.34	0	0.0000
0.34 – 0.36	0	0.0000
0.36 – 0.38	0	0.0000
0.38 -0.40	0	0.0000

Table 4-17. REEDM Predicted Exhaust Cloud Transport Directions For Daytime Taurus II Static Test Firing Scenarios.

Plume Transport Direction Bin	Count	Probability
337.5 – 22.5 (N)	397	0.084
22.5 – 67.5 (NE)	832	0.177
67.5 – 112.5 (E)	838	0.178
112.5 – 157.5 (SE)	955	0.203
157.5 – 202.5 (S)	489	0.104
202.5 – 247.5 (SW)	440	0.094
247.5 – 292.5 (W)	316	0.067
292.5 – 337.5 (NW)	437	0.093

Similar summary tables for the 1728 nighttime Taurus II static test firing simulations were compiled. Table 4-18 shows that the peak CO instantaneous concentration predictions for nighttime conditions continues with a high probability that the maximum far field concentration will be less than 1 ppm.

Table 4-18. REEDM Predicted Maximum Far Field Ground Level Carbon Monoxide Concentrations For Nighttime Taurus II Static Test Firing Scenarios.

Concentration Bin	Count	Probability
0 - 1	1231	0.712
1 - 2	279	0.161
2 - 3	99	0.057
3 - 4	42	0.024
4 - 5	33	0.019
5 - 6	15	0.009
6 - 7	9	0.005
7 - 8	9	0.005
8 - 9	3	0.002
9 +	3	0.002

The REEDM static test firing predicted CO 1-hour time weighted average concentrations for all nighttime meteorological cases is provided in Table 4-19 and it is noted that approximately 59% of all nighttime meteorological cases resulted in REEDM maximum 1-hour TWA ground level

CO concentrations of less than 0.04 ppm. Static test firing TWA CO concentrations trend higher than those observed in the normal launch simulations.

Table 4-20 indicates the predicted Taurus II static test firing plume direction probability of occurrence observed across the 1728 nighttime balloon soundings. It is noted that for nighttime launch scenarios transport of the exhaust plume to the East is still favored as it was during the daytime.

Table 4-19. REEDM Predicted Maximum Far Field Ground Level Carbon Monoxide TWA Concentrations For Nighttime Taurus II Static Test Firing Scenarios.

1-Hour TWA Concentration Bin	Count	Probability
0.00 – 0.02	605	0.350
0.02 – 0.04	407	0.236
0.04 - 0.06	293	0.170
0.06 - 0.08	197	0.114
0.08 - 0.10	84	0.049
0.10 - 0.12	58	0.034
0.12 - 0.14	31	0.018
0.14 - 0.16	9	0.005
0.16 - 0.18	19	0.011
0.18 – 0.20	11	0.006
0.20 – 0.22	7	0.004
0.22 – 0.24	3	0.002
0.24 – 0.26	2	0.001
0.26 – 0.28	0	0.000
0.28 – 0.30	1	0.001
0.30 – 0.32	1	0.001
0.32 – 0.34	0	0.0000
0.34 – 0.36	0	0.0000
0.36 – 0.38	0	0.0000
0.38 -0.40	0	0.0000

Table 4-20. REEDM Predicted Exhaust Cloud Transport Directions For Nighttime Taurus II Static Test Firing Scenarios.

Plume Transport Direction Bin	Count	Probability
337.5 – 22.5 (N)	72	0.042
22.5 – 67.5 (NE)	321	0.186
67.5 – 112.5 (E)	306	0.177
112.5 – 157.5 (SE)	378	0.219
157.5 – 202.5 (S)	221	0.128
202.5 – 247.5 (SW)	207	0.120
247.5 – 292.5 (W)	92	0.053
292.5 – 337.5 (NW)	131	0.076

4.4 REEDM Near Field Results For Taurus II Normal Launch Scenario

In REEDM terminology the "near field" is defined as the geographical region near the launch pad where the rocket exhaust cloud source is formed and undergoes vertical cloud rise due to buoyancy effects. REEDM is not specifically designed to predict cloud concentrations in this region because the area is typically evacuated during launches due to high risk from debris, blast, fire and toxics hazards. Emissions in this region are of interest for environmental considerations however; therefore ACTA modified the output of REEDM to report intermediate calculations of the exhaust cloud size, position and temperature during the cloud rise phase. Using information about the size and location of the exhaust cloud coupled with the known quantity of exhaust products emitted and the mass fractions of the exhaust chemical constituents allows an estimate to be made of chemical concentrations inside the cloud in the near field. When performing far field calculations, REEDM assumes that the mass distribution of exhaust products in the expanded and diluted exhaust cloud is Gaussian. In the near field, as the source cloud is initially formed, the exhaust products may be more uniformly distributed. ACTA computed in-cloud concentrations in the near field assuming both uniform and Gaussian mass distributions. For the Gaussian distribution the maximum concentration occurs at the cloud centroid and the edge of the cloud is defined as the point where the concentration is 10% of the centroid maximum values. This assumption defines the cloud radius as 2.14 standard deviations.

The size and shape of the near field ground level carbon monoxide concentration pattern depends upon several factors:

1. The dynamics of the exhaust flow emitted from the Taurus II Pad-0A flame duct.

2. The effects of thermal buoyancy that lifts the plume off the ground and imparts vertical acceleration to the hot plume gases.

3. The effect of local wind speed and direction after the jet momentum has dissipated and the plume is beginning to lift off the ground.

The jet dynamics of the high speed exhaust plume venting from the flame duct are largely independent of the weather conditions and are determined by the design of the flame duct and concrete ramp structure at the exit of the duct. These design features were still in development and evaluation at the time of this study. The vertical rise rate of the buoyant cloud after the jet dynamics have dampened are computed by REEDM and were used to estimate the vertical and horizontal cloud displacement from a point where the exhaust plume is assumed to become buoyancy dominated. For normal launches, only a portion of the main engine exhaust vents through the flame duct and some of the ground cloud forms around the launch pad. A detailed computational fluid dynamics flow analysis of the plume interaction with the flame duct and the launch pad surface is not available, however, based on photographs and video of other launch vehicle normal launch ground clouds, it is estimated that the center of the Taurus II normal launch ground cloud will be displaced about 100 meters from the vehicle liftoff position in the direction of the flame duct exit.

REEDM calculations for the near field normal launch cloud rise were processed for 6427 meteorological cases and summarized by month as shown in Table 4-21. REEDM approximates the Taurus II normal launch ground cloud as a sphere the radius of which grows linearly during the buoyant cloud rise phase according to the following relationship:

$$r(z) = r_0 + \gamma \Delta z$$

where:

$r(z)$	=	cloud radius at height z [m]
r_o	=	initial cloud radius [m] = 48.8 [m] (160 ft)
γ	=	air entrainment coefficient = 0.36
Δz	=	height of cloud centroid above the ground [m]

Based on the forgoing relationship, the spherical cloud will just touch the ground surface when the cloud centroid lifts to approximately 76 meters above the ground. This is also referred to in this report as the “cloud liftoff” point. Beyond this point the downwind ground CO concentration is assumed to be zero until the ground concentrations once again start to occur in the far field due to downward mixing from the stabilized normal launch cloud. The maximum distance from the point where the flame duct horizontal flow dynamics are dampened (REEDM initialization point) to the point where the wind driven normal launch plume lifts off the ground is estimated to be 144 meters. Average distance from the REEDM initialization point to the point of cloud liftoff is estimated to be about 25 meters. These distances are influenced by the initial amount of cloud "exhaust" materials as well as the air entrainment rate assumption. If deluge water injection and combustion air are added to the initial exhaust mass, then the initial cloud radius will be larger and the downwind distance to the liftoff point will be somewhat longer. Given uncertainties in the plume mass entrainment and other modeling assumptions, the maximum travel distance to Taurus II normal launch ground cloud liftoff is estimated at about 200 meters. Thus a circle with a radius of 200 meters centered 100 meters downstream from the flame duct exit would approximately define the region within which a toxic exposure to CO might occur under high surface wind conditions. The average potential toxic exposure zone is expected to be much smaller and is associated with moderate to light surface winds. Maximum ground level CO concentrations inside the near field toxic hazard zone could exceed 7000 ppm.

Table 4-21. Taurus II Normal Launch Near Field CO Concentration Summary.

Month	Number of Weather Cases	Ground CO Concentration at Cloud Liftoff Uniform Distribution [ppm]	Ground CO Concentration at Cloud Liftoff Gaussian Distribution [ppm]	Maximum Distance to Cloud Liftoff [m]	Average Distance to Cloud Liftoff [m]
January	435	7530	1980	78	22
February	521	7420	1950	86	23
March	559	7190	1890	99	25
April	538	8440	2220	93	25
May	556	7250	1910	86	23
June	544	7140	1880	55	21
July	569	6650	1750	62	20
August	570	7790	2050	61	18
September	576	7190	1890	144	21
October	554	7330	1930	98	19
November	507	7870	2070	101	20
December	498	8280	2180	76	22

An example of near field concentration calculations for a normal launch plume with a May meteorological case that produced a low cloud rise is listed below. As the ground cloud rises REEDM assumes it intersects and combines with the contrail cloud above it and the total amount of exhaust mass in the rising cloud continues to increase until the ground cloud stops rising at the stabilization altitude. As previously defined, when the predicted ground cloud radius just equals the height of the ground cloud centroid above the ground, the exhaust cloud is just at the point of lifting off the ground. In Table 4-22 this occurs as the cloud rises through the 8th meteorological layer where the top of the layer is 89.9 meters above the ground and the cloud radius is predicted to be 80.8 meters. At this point the cloud is predicted to have moved 20.6 meters in the downwind direction, has an average temperature of 329.5 Kelvin (133 F) and has an uniform CO concentration of 7615 ppm. As the cloud continues to move downwind it rises further above the ground and only flying birds or tall trees would be exposed to the concentrated cloud exhaust chemicals. This sample normal launch cloud is predicted to stabilize at 440 meters above the ground approximately 200 meters downwind from the initial source formation point and has a predicted radius of 206.9 meters. The bottom of the exhaust cloud would be approximately 233 meters above the ground. The centroid concentration, assuming the mass distribution has transitioned to Gaussian, is predicted to be 3881 ppm with the concentration at the edge of the cloud equal to 388 ppm (10% of the peak centroid concentration).

Table 4-22. Sample Near Field Taurus II Normal Launch Exhaust Cloud Concentration Estimates For a May WFF Meteorological Case.

initial cloud radius [m] = 48.76800
initial cloud height [m] = 0.0000000E+00
initial cloud rise velocity [m/s] = 0.0000000E+00

met layer	cloud height [m]	cloud radius [m]	cloud volume [m**3]	exhaust mass [g]	downwind dist [m]	rise time [sec]	cloud temp [K]	uniform conc [ppm]	Gaussian conc [ppm]
1	11.0	52.4	.60123E+06	.17505E+08	2.3	1.295	590.5	6516.	17152.
2	20.6	55.8	.72845E+06	.23196E+08	5.8	0.632	498.6	7127.	18760.
3	30.2	59.3	.87234E+06	.30021E+08	8.0	0.580	443.6	7703.	20275.
4	39.8	62.7	.10341E+07	.37721E+08	10.1	0.573	407.6	8164.	21489.
5	49.4	66.2	.12148E+07	.46158E+08	12.2	0.584	382.5	8504.	22384.
6	59.3	69.8	.14221E+07	.55242E+08	14.4	0.622	363.7	8694.	22884.
7	69.2	73.3	.16517E+07	.64928E+08	16.7	0.647	349.6	8798.	23158.
8	89.9	80.8	.22091E+07	.75165E+08	20.6	1.451	329.5	7615.	20044.
9	108.5	87.5	.28051E+07	.86432E+08	26.0	1.423	317.9	6896.	18152.

10	126.5	94.0	.34754E+07	.98520E+08	31.5	1.490	310.0	6345.	16701.
11	144.5	100.4	.42446E+07	.11134E+09	37.3	1.605	304.2	5871.	15453.
12	176.0	111.8	.58536E+07	.12482E+09	46.4	3.091	297.9	4773.	12563.
13	207.6	123.2	.78254E+07	.13940E+09	59.1	3.425	294.1	3987.	10494.
14	222.5	128.5	.88963E+07	.15495E+09	69.4	1.734	292.7	3898.	10261.
15	240.2	134.9	.10285E+08	.17095E+09	77.2	2.141	291.2	3720.	9792.
16	295.4	154.8	.15530E+08	.18744E+09	96.9	7.536	288.8	2701.	7111.
17	339.9	170.8	.20869E+08	.20538E+09	127.3	7.224	287.6	2203.	5798.
18	386.5	187.6	.27649E+08	.22438E+09	158.3	9.055	286.9	1816.	4781.
19	440.1	206.9	.37099E+08	.24441E+09	198.2	14.517	286.9	1475.	3881.

4.5 REEDM Near Field Results For Taurus II Static Test Firing Scenario

REEDM calculations for the near field static test firing cloud rise were processed for 6427 meteorological cases and summarized by month as shown in Table 4-23. REEDM approximates the Taurus II static test firing cloud as a sphere the radius of which grows linearly during the buoyant cloud rise phase according to the following relationship:

$$r(z) = r_0 + \gamma \Delta z$$

where:

$r(z)$	=	cloud radius at height z [m]
r_o	=	initial cloud radius [m] = 46.05 [m] (151 ft)
γ	=	air entrainment coefficient = 0.5
Δz	=	height of cloud centroid above the ground [m]

Based on the forgoing relationship, the spherical cloud will just touch the ground surface when the cloud centroid lifts to approximately 91 meters above the ground. The initial cloud radius is calculated using the ideal gas law and the principle of mass conservation applied to the engine RP-1 and LOX propellant consumed in the test firing. Inclusion of deluge water and combustion air injected beyond the nozzle exit plane would increase the cloud exhaust mass and therefore would also increase the estimated initial cloud radius.

Table 4-23. Taurus II Static Test Firing Near Field CO Concentration Summary.

Month	Number of Weather Cases	Ground CO Concentration at Cloud Liftoff Uniform Distribution [ppm]	Ground CO Concentration at Cloud Liftoff Gaussian Distribution [ppm]	Maximum Distance to Cloud Liftoff [m]	Cloud Transport Bearing Associated With Max Cloud Liftoff [deg]	Average Distance to Cloud Liftoff [m]
January	435	3990	1050	212	181	36
February	521	3980	1050	249	298	40
March	559	4010	1055	299	269	43
April	538	3960	1040	271	316	43
May	556	4050	1065	259	302	38
June	544	3980	1050	126	328	33
July	569	4020	1060	161	101	31
August	570	4020	1060	143	333	27
September	576	3970	1040	557*	298	36
October	554	3960	1040	296	309	30
November	507	4050	1065	307	310	33
December	498	4020	1060	211	283	36

* September case with 557-meter downwind distance was under storm conditions with 60 knot surface winds, an unlikely weather condition for conducting a test firing.

Given uncertainties in the static test firing plume mass entrainment and other modeling assumptions, the maximum travel distance to Taurus II static test firing cloud liftoff is estimated at about 350 meters. Thus a circle with a radius of 350 meters centered 200 meters downstream from the flame duct exit would approximately define the region within which a toxic exposure to CO might occur under high surface wind conditions. The average potential toxic exposure zone is expected to be much smaller and is associated with moderate to light surface winds. Maximum ground level CO concentrations inside the near field static test firing toxic hazard zone could exceed 4000 ppm.

5. CONCLUSIONS

A conservative analysis approach has been applied to estimate carbon monoxide concentrations associated with Taurus II normal launch and static test firing scenarios. The analysis is deemed to be conservative in the sense that certain modeling assumptions, such as discounting the effect of uncertain processes such as the plume chemical alterations due to deluge water injection and plume afterburning with ambient air, favor predicting higher carbon monoxide concentrations than are expected to actually occur. The study also evaluated maximum chemical concentrations predicted using a set of over 6000 historical Wallops Flight Facility weather balloon soundings. Thus reasonable worst-case weather conditions should have inherently been captured in the study. The Taurus II first stage propellants are the hydrocarbon based fuel RP-1 and liquid oxygen (LOX). Under design combustion conditions the oxidizer to fuel burn ratio is approximately 2.7, which represents a somewhat fuel rich mixture. The main combustion byproduct of concern is carbon monoxide, which is estimated to comprise approximately 25.6 percent of the exhaust mixture by mass at the rocket nozzle exit. The other main combustion byproducts are carbon dioxide and water vapor. Rocket emissions from both the a normal vehicle launch and a static test firing on the launch pad are extremely hot and therefore less dense than surrounding ambient air and are accelerated vertically due to buoyancy forces that act on the exhaust cloud gases. The effect of buoyancy is to loft the exhaust clouds above the ground to a point of neutral stability in the atmosphere at altitudes ranging from 400 to 1300 meters above the ground. From the stabilization altitude, exhaust cloud materials eventually mix back down to the ground due to atmospheric turbulence, unless the entire cloud is predicted to rise above a capping thermal inversion. The geographic region near the launch pad where the source cloud forms and begins its thermal rise process is referred to as the “near field”. Ground level CO concentrations in the near field region are estimate to be in the 4000 to 20000 ppm range, however the downwind transport distance before the cloud lifts off the ground is predicted to be relatively short—on the order of several hundred meters or less. The geographic region where the stabilized and neutrally buoyant cloud material mixes back to the ground is referred to as the “far field”. REEDM predicts that the peak instantaneous CO concentrations in the far field region are typically less than 1 ppm but have the potential to reach as high as 20 ppm. One-hour time weighted average CO concentrations are estimated to be very low, typically less than 0.04 ppm, and these low TWA values are due to the short cloud passage time over a receptor location (e.g. minutes rather than hours). The far field CO concentration levels are well below published emergency exposure guidelines for humans and are considered to be benign to people, flora and fauna. Near field CO concentrations may reach hazardous levels that exceed the AEGL-3 10-minute exposure threshold or the IDLH exposure threshold. Given the proximity of the near field exposed region to the plume point of origin, other hazards, such as radiant heat transfer or direct exposure to the high temperature exhaust gas mixture, may be more severe than the hazard from CO chemical concentration exposure.

6. REFERENCES

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