Inhalation of Fugitive Dust:

A Screening Assessment of the Risks Posed by Coal Combustion Waste Landfills

DRAFT

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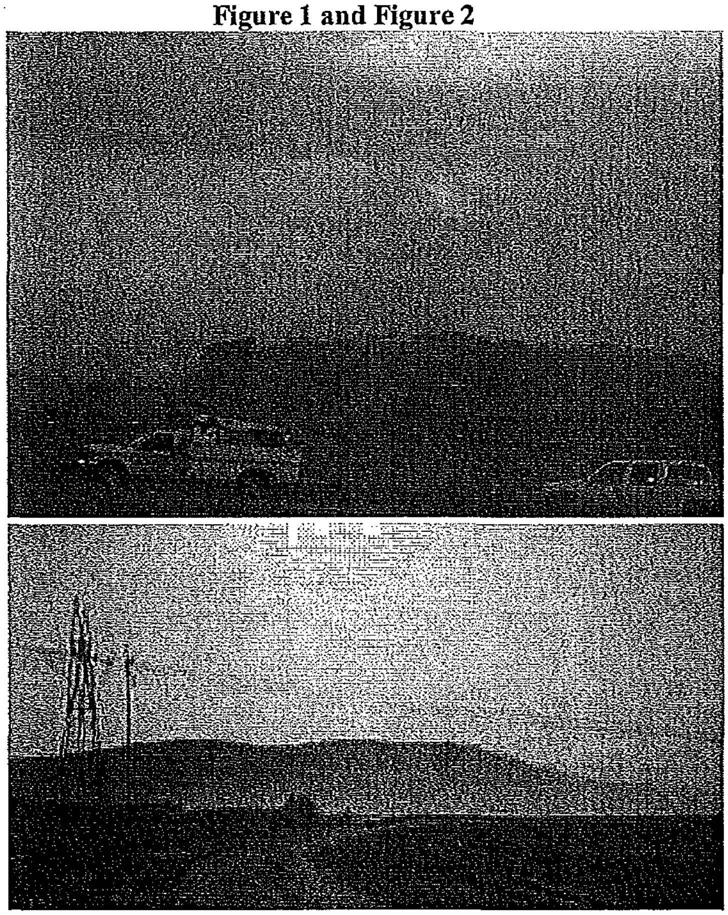
1.0 Introduction

Inhalation of Fugitive Dust is intended to be a companion document to the U.S. Environmental Protection Agency's (EPA) 2009 *Human and Ecological Risk Assessment of Coal Combustion Wastes* (U.S. EPA, 2009). In 2007, EPA released its draft risk assessment (U.S. EPA, 2007). This document was released to a panel of five peer reviewers, and to the public via a notice of data availability (NODA) in the Federal Register.[1] In both the peer review and NODA, EPA received comments regarding fugitive dust. These comments pointed out that fugitive dust emissions during the operation of a coal combustion waste (CCW) management unit (WMU) were not addressed in the draft risk assessment (RA). However, since there was anecdotal evidence that fugitive dust was often emitted from WMUs, EPA decided to examine the potential for uncontrolled emissions from dry handling to lead to significant human health risks.

Figure 1 and Figure 2



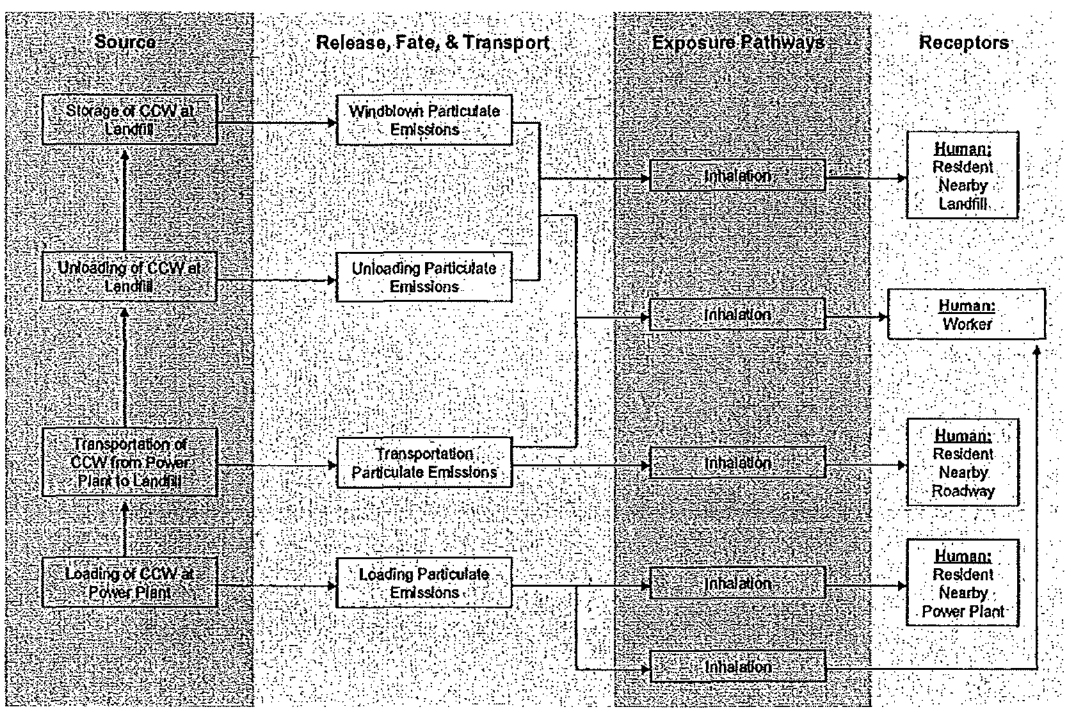
Fugitive dust associated with CCW landfilling operations.
Top: Gambrills, MD; ***Bottom:*** *Four Corners, NM.*[2]

[1] Docket ID: EPA-HQ-RCRA-2006-0796. Document ID: EPA-HQ-RCRA-2006-0796-0042.
[2] Photos courtesy of Lisa Evans, Earthjustice

2.0 Inhalation of CCW Emitted from Landfilling Operations

When dry-handled, CCW will be emitted into the air by loading, transport, unloading, and wind erosion. Once in the air, it will likely migrate off-site as fugitive dust. As a result, workers and nearby residents could be exposed to significant amounts of coarse particulate matter (PM_{10}) and fine particulate matter ($PM_{2.5}$). The purpose of this assessment is therefore to assess whether the national ambient air quality standards (NAAQS) for particulate matter could be violated through CCW landfilling operations[3] without fugitive dust controls. This will be accomplished through a conservative screening analysis. Figure 3 below shows the conceptual model for the type of landfilling operation relevant here. If the inhalation pathway cannot be screened out, then it is possible for fugitive dust to pose a threat to human health, and regulation addressing fugitive dust should be considered. Conversely, if the inhalation pathway can be screened out, then it is highly unlikely that the inhalation of particulates from CCW landfills poses a significant risk to human health. However, there are two uncertainties inherent in this bright line screen evaluated in this report. First, there may be background levels of particulates which, when added to the levels calculated here may still pose significant risks. Second, it would still be possible for constituents adsorbed onto CCW particulates to pose a risk to human health. This screening evaluation does not address either background levels of particulates or a constituent-based exposure pathway.

Figure 3 – Fugitive Dust Conceptual Model for Dry Handling of CCW



[3] This does not include activities such as minefilling, reclamation of sand and gravel pits, or beneficial use.

2.1 Initial Scenario

Three groups of residents are likely to be exposed to fugitive dust as a result of the dry handling of CCW.[4] Residents living near a coal power plant could be exposed to emissions resulting from loading of the CCW. Residents near roads could be exposed to emissions during transportation. Finally, residents living near CCW landfills could be exposed from both the unloading and windblown emissions.

Residents living near a CCW landfill will often be exposed to more fugitive dust, and for longer periods of time, than those living near the roads or power plants themselves. This is the case because these residents would be exposed to emissions from both unloading of CCW and windblown emissions of CCW. Thus, only the residents living near CCW landfills will be considered further as they represent a highly exposed population. In addition, as a landfill gets closer to capacity, the less relative influence unloading emissions would have on total emissions. In the preliminary scenario considered, the entire landfill is left exposed to wind until the end of its useful life. Thus, windblown emissions could be considered representative of total emissions as they would dominate.

To estimate the concentration of fugitive dust in the air near a CCW landfill, the SCREEN3 model was used.[5] SCREEN3 (a screening version of ISC3) is a single source Gaussian plume model which provides maximum ground-level concentrations for point, area, flare, and volume sources. It was developed to provide an easy-to-use method of obtaining pollutant concentration estimates based on *Screening Procedures for Estimating the Air Quality Impact of Stationary Sources* (U.S. EPA, 1995c). A technical description of the SCREEN3 model is provided in Appendix E. The SCREEN3 outputs will then be compared to the relevant NAAQS as presented in Table 1 below.

Table 1 – NAAQS for Particulate Matter

Pollutant	Standard	Averaging Time
PM_{10}	150 $\mu g\ m^{-3}$	24-hour
$PM_{2.5}$	15.0 $\mu g\ m^{-3}$	Annual
$PM_{2.5}$	35 $\mu g\ m^{-3}$	24-hour

See 40 C.F.R. 50[6]

2.2 Emission Factors

In order to model the concentration of the particulate matter in the air, it is necessary to estimate the emission rate for the CCW managed in landfills. A point estimate for the windblown emission factor was calculated below using the equation for "Continuous Fugitive/Windblown Dust Emissions" (U.S. EPA, 1992):

[4] Workers who handle CCW would also be exposed to fugitive dust, but they are protected by OSHA regulations.
[5] SCREEN3 is publicly available at http://www.epa.gov/scram001/dispersion_screening.htm
[6] NAAQS available at http://www.epa.gov/air/criteria.html

$$E = 1.9\left(\frac{s}{1.5}\right)\frac{(365-p)}{235}\left(\frac{w}{15}\right)$$

where:

E = emission factor (kg d^{-1} ha^{-1})
s = material silt content (%)
p = number of days per year with more than 25 mm of precipitation (N/A)
w = percent of time wind speed exceeds 5.4 m s^{-1} (%)

The material silt content of 80% for fly ash was taken from Table 13.2.4-1 in AP-42, chapter 13 (2006). The default values in the workbook (U.S. EPA, 1992) of 0 for p and 20% for w were used in calculating this emission factor. The result (209.85 kg d^{-1} ha^{-1}) was converted to g s^{-1} m^{-2}, with a final emission rate of 2.43×10^{-4} g s^{-1} m^{-2}. While there are likely a range of emission factors, this screening assessment was not designed to evaluate all possible fugitive dust scenarios. Rather, the purpose is only to see if fugitive dust from dry-handling of CCW would likely pose a significant risk to human health. Thus, EPA believes its use of a best estimate emission factor is appropriate.

2.3 Length/Width, Distance to Receptor

Two other factors necessary to model fugitive dust are the length/width of the landfill and the distance to the receptor. Unlike the emission factor, EPA decided to use a range for these inputs. While it would have been possible to use a point estimate, there were orders of magnitude of difference between the smallest and largest CCW landfills and between the shortest and furthest distances to receptors. Thus, EPA used a range of percentiles to model the upper end of particulate matter that could reasonably be expected in the air breathed by a receptor. In keeping with the conservative nature of this assessment, the 50th through 90th percentiles of size and 10th through 50th percentiles of distance were used. The maximum size and minimum distance were excluded as they would be too conservative to be considered reasonable.

To be as realistic as possible, EPA based the landfill dimensions on actual CCW landfill data provided by the Council of Industrial Boiler Owners (CIBO, 1997) and Electric Power Research Institute (EPRI, 1997). Of the data available in those reports, 124 WMUs were landfills. These landfills were arranged to form a size distribution (in acres), and percentiles were calculated. These can be seen in Table 2 below. These distributions were converted from acres into square meters. The assumption was then made that the landfills were square. This allowed the calculation of the length and width of the landfills, reported as the side length in Table 2 below. For a further discussion of the landfill size distribution, see Appendix A – Landfill Size Data.

Table 2 – Distribution of Landfill Sizes

Percentile	in Acres	in m^2	side length (m)
50th	66.5	269,116	518.8
60th	85.0	343,983	586.5
70th	121.4	491,288	700.9
80th	208.4	843,365	918.3
90th	297.6	1,204,344	1,097.4

Raw data and percentiles are provided in Appendix A.

Distance to the nearest receptor, on the other hand, was not based on actual CCW landfill distances as no such data exists. While EPA acknowledges that this data would be useful, there is not sufficient time and resources to collect this data. Instead, because the receptors of interest are residents living near a CCW landfill, it is assumed that the distribution of closest receptors here would be the same as the distribution used in the RA. These can be seen in Table 3 below. For a further discussion of the landfill size distribution, see Appendix B – Distance to Receptor Data.

Table 3 – Distribution of Receptor Distances

Percentile	Distance (m)
10th	104
20th	183
30th	305
40th	366
50th	427

Further discussion and percentiles are provided in Appendix B.

Taken together, the combinations of sizes and distances to be modeled will attempt to provide both a true median (50th, 50th) and upper tail (90th, 10th) of the input distribution that would be modeled in a probabilistic assessment. Thus, although the model itself has a conservative bias, the results endeavor to present both a typical and upper tail risk.

2.4 Other Input Parameters for SCREEN3

In addition to the emission rates, the following input parameters are also required for the SCREEN3 modeling runs.

- Source Type: Area was chosen because the emissions would be coming off a landfill and not from a smokestack or other point source.
- Height of CCW Landfill: A height of 0m was chosen based on the assumption that the landfill would be dug into the ground, and not elevated. It was also a conservative assumption as elevated landfills actually generate lower particulate matter emissions for nearby receptors. This issue is addressed further in Appendix C.
- Receptor Height: 1.75m was chosen to be protective of a typical human receptor. (This is approximately the height in meters of a 5'9" individual.) This assumption is addressed further in Appendix C.
- Urban or Rural: Rural was chosen because CCW landfills are much more likely to be located in a rural setting. In addition, it is more conservative than the urban option. This issue is addressed further in Appendix C.
- Search for Maximum Direction: A positive setting was chosen as a conservative assumption so that the maximum air concentration would be located.

SCREEN3 requires the user to specify the modeling area. This area is the range of distances from the center of the source where SCREEN3 will estimate maximum concentrations. For this study, the modeling area was defined as the region from 0 to 1,500m (just under a mile) from the center of the source to ensure that the 50th percentile distance listed above would be included. In addition, there is a user option to specify discrete distances. These are specific distances from the center of the source where the user can request SCREEN3 to estimate maximum concentrations. This specific distance is the distance to the receptor that is chosen from the distribution in Table 3 above.

Table 4 – Input parameters for SCREEN3

Parameter Description	Value
Source type	Area
Emission rate (g/s-m^2)	0.000243[1]
Height of storage pile (m)	0
Length of storage pile (m)	Variable[2]
Width of storage pile (m)	Variable[2]
Receptor height (m)	1.75
Urban or Rural	Rural
Search for maximum direction	Yes
Choice of meteorology	Full
Automated distance array	Yes
Minimum distance (m)	0
Maximum distance (m)	1500
Use discrete distances	Yes
Distance (m)	Variable[3]

[1] Calculated using the workbook (U.S. EPA, 1992)

[2] Based on EPRI landfill size data (EPRI, 1995)

[3] Based on landfill to well distances (U.S. EPA, 1988)

2.5 SCREEN3 Outputs

Using the inputs listed in Table 2, 3, and 4, SCREEN3 was used to estimate the concentration of CCW in the air at ground level under the windblown erosion scenario. After running the model with both 50th percentile values plugged in, a result of 13,390μg m^{-3} was obtained. Since the values generated by SCREEN3 are maximum values, they should be compared to the 24-hour NAAQS. However, even under the assumption that 100% of the CCW was PM_{10}, this would still violate the 24-hour NAAQS for PM_{10} of 150 μg m^{-3} by nearly two orders of magnitude. This indicates that the risks posed by fugitive dust cannot be screened out if no dust controls are applied before closure, and therefore it was unnecessary to run the screen with other percentiles.

3.0 Secondary Scenarios

Given that the risks of uncontrolled fugitive dust emissions could not be screened out, the next logical question was whether or not the risks given particular management options could be screened out. Perhaps covering or spraying the CCW on a regular basis to prevent emissions could be adequate to protect human health. The appropriate question then is how frequently these controls should be applied to ensure the NAAQS are not exceeded. Some possible time frames might be yearly, monthly, weekly, and daily. To model these scenarios, caveats and additional information are required. First, assuming that a landfill is operated consistently over its life time, the life will affect how much of the landfill is being used over any period of time. In a previous groundwater risk assessment, EPA estimated that the operating life of a CCW landfill is 40 years (U.S. EPA, 1998a). EPA believes that this is still an accurate estimate, and thus, it is assumed for this assessment that all landfills will operate for 40 years. Since a landfill is assumed to operate consistently over a 40-year life, then the area of the landfill that is operated during any year can be stated as:

$$A_{yr} = \frac{A_{total}}{40}$$

where:

A_{yr}	=	the area of the landfill in use over a year (m^2)
A_{total}	=	the total landfill capacity (m^2)
40	=	life of a CCW landfill (N/A)

Once the portion of the WMU used over a single year is estimated, then it is also possible calculate the area of the landfill used monthly, weekly, and daily as follows:

$$A_{month} = \frac{A_{yr}}{12} \qquad A_{wk} = \frac{A_{yr}}{52} \qquad A_{d} = \frac{A_{yr}}{365}$$

where:

A_{month}	=	the area of the landfill in use over a month (m^2)
A_{wk}	=	the area of the landfill in use over a week (m^2)
A_{d}	=	the area of the landfill in use over a day (m^2)
A_{yr}	=	the area of the landfill in use over a year (m^2)
12	=	the number of months in one year (N/A)
52	=	the number of weeks in one year (N/A)
365	=	the number of days in one year (N/A)

Performing these calculations on each percentile from Table 2 above, the areas and side lengths for the portion of the WMU operated over each period of time is as follows:

Table 5 – Area (m^2) and Side (m) Distributions

	Yearly		Monthly		Weekly		Daily	
%ile	Area	Side	Area	Side	Area	Side	Area	Side
50th	6,728	82.0	561	23.7	129	11.4	18	4.3
60th	8,600	92.7	717	26.8	165	12.9	24	4.9
70th	12,282	110.8	1024	32.0	236	15.4	34	5.8
80th	21,084	145.2	1757	41.9	405	20.1	58	7.6
90th	30,109	173.5	2509	50.1	579	24.1	82	9.1

All values based on assumption that a WMU operates consistently for 40 years.

Here again, the size of the operating portion of the landfill is assumed to be a square, so each side is the square root of the area. One final assumption that must be made is the location of this operating portion of the landfill with respect to the receptor. For simplification, it will be assumed that the operating portion is in the very center of the landfill. Using the center will give results that estimate an average concentration over the entire lifetime of the landfill for a receptor located in any direction. This assumption is consistent with EPA's previous risk assessment where the air pathway was modeled (U.S. EPA, 1998b).

3.1 Model Runs and Outputs

The model was first run entering the 50th percentile values for both side length and distance to receptor. If this median exposure could not be screened, then higher risk scenarios were not evaluated. The results of these screens are presented in Table 6 below.

Table 6 – Median Scenario Outputs ($\mu g\ m^{-3}$)

Period	Particulates	Pass Screen?[1]
Yearly	1388	NO
Monthly	159.4	NO
Weekly	38.0	YES
Daily	5.4	YES

[1] The screen was passed if the NAAQS would not be exceeded.

Since weekly and daily controls for fugitive dust passed the screen using the median scenario inputs, further permutations of inputs were entered into the model to determine the likelihood that operating with this frequency of controls would be adequate to protect human health. These results are reported in Tables 7 and 8 below.

Table 7 – SCREEN3 Outputs ($\mu g\ m^{-3}$), Weekly Fugitive Dust Controls

	Distance to Nearest Receptor				
Landfill Size	50th	40th	30th	20th	10th
50th	38.0	44.3	52.5	78.3	107.5
60th	44.9	51.9	60.9	88.4	118.4
70th	56.6	64.3	74.2	104.0	134.6
80th	78.0	87.1	98.1	129.1	***159.5***
90th	95.9	105.9	117.8	149.1	***178.4***

See Appendix D for raw inputs and outputs.

Table 8 – SCREEN3 Outputs ($\mu g\ m^{-3}$), Daily Fugitive Dust Controls

	Distance to Nearest Receptor				
Landfill Size	50th	40th	30th	20th	10th
50th	5.4	6.4	7.6	11.3	15.7
60th	6.5	7.6	8.9	13.0	17.6
70th	8.1	9.2	10.7	15.1	19.7
80th	11.3	12.7	14.3	19.0	23.6
90th	13.9	15.42	17.2	21.9	26.4

See Appendix D for raw inputs and outputs.

4.0 Results and Discussion

As seen in Tables 6, 7, and 8, the risks posed by fugitive dust inhalation could not be screened out for every management time frame. However, certain conclusions can be drawn for each management consideration. The discussion of each time frame is below, but should be interpreted with several overarching uncertainties in mind.

- The SCREEN3 model is a conservative screening model. Thus, in most instances, the levels of particulate matter calculated here are likely higher than they actually would be.
- As the area of the landfill exposed to wind erosion decreases due to more frequent controls, unloading emissions would become a much more significant proportion of total emissions. Hence, the more frequently controls are used, the more important it would be to include unloading emissions to calculate an accurate concentration.
- Background levels of particulates were not factored into these calculations. Thus, the particulates calculated here could actually underestimate total particulates.
- The distances to the nearest receptor are not based on recent CCW landfill survey data and may therefore lead to an underestimate or overestimate of particulate levels.
- In the secondary scenarios, the operating portion of the landfill was assumed to be in the center of the landfill and not on the downwind edge. This may lead to an underestimate of particulate levels when that edge portion is used.
- A single emission factor was calculated based on national default inputs. For particular sites, the calculated emission factor could be higher or lower.

Finally, there are a few general trends between the inputs and outputs examined in Appendix C. With respect to the location of WMUs, those located in rural settings will cause much higher particulates concentrations than those in urban settings. Since a rural setting was assumed here, it is possible that some WMUs would present much lower risks to human health through the inhalation of fugitive dust. In addition, it was shown that landfills that are built up, as opposed to dug into the ground, would actually lead to lower particulates concentrations nearby. Thus, in the case of built up landfills, nearby residents would be presented with less risk than what was modeled here. However, receptors may be at ground level, presenting slightly higher risks.

4.1 Controls Applied Yearly

Even at the median risk, yearly management leads to a PM_{10} concentration almost an order of magnitude above the NAAQS. Although larger landfills and closer receptors were not modeled, they would have resulted in even higher exceedences. Therefore, controls applied only at the end of each operating year fail the screen, and have the potential to pose a significant risk to human health.

4.2 Controls Applied Monthly

At the median risk, monthly management leads to a PM_{10} concentration barely above the NAAQS. Although larger landfills and closer receptors were not modeled, they too would have resulted in exceedences. Consequently, controls applied each operating month fail the screen as run, and have the potential to pose a significant risk to human health.

4.3 Controls Applied Weekly

At the median risk, weekly management did not exceed the NAAQS for PM_{10}. Only if most or all of the particulates were $PM_{2.5}$ would there be any exceedance. However, this is not the case because CCW typically consists of only a few percent of $PM_{2.5}$ (EPRI, 1995). When larger landfills and closer receptors were modeled, most did not result in excess risk. Only when receptors were within the closest 10% of the distribution (within about 100m), and landfill sizes were large (over about 200 acres) did levels above the NAAQS result. Thus, in isolation, it is relatively likely that the median would not lead to excessive levels of particulates but that the upper tail could. Thus, the results are mixed, and it is uncertain whether these emissions alone would have the potential to pose a significant risk to human health.

4.4 Controls Applied Daily

At the median risk, daily management did not exceed the NAAQS for PM_{10} or $PM_{2.5}$. Even when larger landfills and closer receptors were modeled, most concentrations fell well below the NAAQS. Taken in isolation, it is certain that neither the median nor the upper-tail scenario would lead to excessive levels of particulates. Thus, without considering background levels, a weekly fugitive dust control would be sufficient to protect human health.

5.0 Conclusion

The purpose of this screening assessment was to determine whether the NAAQS could be violated through dry handling of CCW, and if so, what management options might be appropriate. Indeed, it was found that there is not only a possibility, but a strong likelihood that dry-handling would lead to the NAAQS being exceeded absent fugitive dust controls. Yearly and monthly controls were also found to have the potential to lead to significant risks. However, with this screen, it was uncertain whether weekly controls would have the potential to cause NAAQS exceedences, and even the most conservative evaluation of daily dust controls led to particulate concentrations well below the NAAQS. Thus, without further, more precise evaluation, only daily controls can definitively be said not to cause excess levels of particulates in isolation.

6.0 References

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Appendix A – Landfill Size Data

The source of the data provided below was the compiled data set of CCW landfills and surface impoundments from Appendix B of the RA (U.S. EPA, 2007). That data set was derived from two voluntary industry surveys. The first was an EPRI comanagement survey for conventional utility coal combustion WMUs (EPRI, 1997). The second was a CIBO fluidized bed combustion (FBC) survey for FBC WMUs (CIBO, 1997). The EPRI survey included responses from 323 WMUs. These WMUs served 238 power plants in 36 states, and represented 62 million tons of CCW disposal annually. The CIBO survey included 45 responses from the estimated 84 facilities using FBC technology. While most of these facilities reported beneficially using CCW, 8 of those facilities reported disposing of CCW, and those that landfilled were included in this analysis.

Rank	LF Acres
1	3.4
2	4
3	4.61
4	8
5	9
6	9
7	10
8	11.77391
9	12
10	12
11	13
12	14
13	14
14	15
15	16.4
16	17
17	17
18	18
19	18
20	20
21	20
22	21.3
23	22
24	22
25	22
26	23
27	25
28	25.24
29	25.75
30	26
31	26
32	27
33	28.68322

34	30
35	30
36	30
37	33
38	35
39	36
40	36
41	37
42	38
43	39
44	40
45	40
46	40
47	41.2
48	45
49	45
50	48
51	49.20163
52	51
53	54
54	55
55	57
56	58
57	60
58	60
59	60
60	61
61	61
62	65
63	68
64	68
65	69
66	70
67	70
68	70
69	72
70	79
71	80
72	80
73	85
74	85
75	85
76	96
77	96
78	99
79	100
80	100
81	105

82	106
83	109
84	110
85	112.5
86	120
87	121
88	125
89	125
90	128.6242
91	130
92	150
93	155
94	174
95	176
96	200
97	200
98	200
99	206
100	212
101	220
102	230
103	241
104	246
105	247
106	250
107	250
108	255
109	280
110	290
111	292
112	300
113	300
114	309
115	312
116	315
117	320
118	339
119	400
120	434
121	540
122	596
123	825
124	900

Percentile	in Acres	in m²	side (m)
Min	3.4	13,759	117.3
5th	10.3	41,545	203.8
10th	14.3	57,870	240.6
15th	18.9	76,486	276.6
20th	22.6	91,459	302.4
25th	26.8	108,253	329.0
30th	34.8	140,831	375.3
35th	40.0	161,874	402.3
40th	48.2	195,222	441.8
45th	58.7	237,550	487.4
50th	66.5	269,116	518.8
55th	71.3	288,541	537.2
60th	85.0	343,983	586.5
65th	104.8	423,908	651.1
70th	121.4	491,288	700.9
75th	159.8	646,485	804.0
80th	208.4	843,365	918.3
85th	248.7	1,006,251	1,003.1
90th	297.6	1,204,344	1,097.4
95th	336.2	1,360,351	1,166.3
Max	900.0	3,642,170	1,908.4

Appendix B – Distance to Receptor Data

The residential scenario for the fugitive dust pathway analysis calculates exposure from a CCW landfill's emissions to the air. The receptor distances used were based on the distances used for residential wells in the RA (U.S. EPA, 2007). This assumes that the residence closest to a landfill would be the same residence that has the closest downgradient well. EPA believes this to be an adequately protective assumption since the closest distance is less than a meter, or directly against the edge of a landfill.

The well distances themselves were derived from sampling a nationwide distribution of the nearest downgradient residential well distances taken from a survey of municipal solid waste landfills (U.S. EPA, 1988). EPA recognizes that this is a significant uncertainty in the analysis. Based on an assumption that population densities around CCW landfills are roughly comparable to population densities that existed near the municipal landfills surveyed in U.S. EPA (1988), EPA believes that the MSW well distance distribution is a roughly representative of actual distances between CCW landfills and nearby residences. However, since not all residences have downgradient wells, there could be closer residences in other instances. While further data on the distances to the nearest residence would be useful to the analysis, such data is not readily available at this time.

Distribution of Receptor Distances

Percentile	Distance (m)
Min	0.6
10th	104
20th	183
30th	305
40th	366
50th	427
60th	610
70th	805
80th	914
90th	1,220
Max	1,610

Source: U.S. EPA (1988)

Appendix C – Sensitivity of Results to Inputs

Several assumptions about WMUs were made in Section 2.4. Among these were three assumptions that do not always hold true. The first was that WMUs will be located in rural locations. In fact, some coal power plants are located in or adjacent to major metropolitan areas. Second, it was assumed that the landfills would be dug into the ground, and would therefore have a height of 0m. However, there are landfills that are built up meters or tens of meters. Finally, it was assumed that the receptor was a standing individual of a typical height. Yet, this ignores situations where individuals are sitting, laying down, or even where infants are crawling. Therefore, to ensure that the model remained properly conservative, further runs were conducted to determine what affect (if any) altering these inputs would have on the modeled particulate matter concentrations.

The assumptions made in the actual screen turned out to be conservative, with the exception of the receptor height. As seen in the table below, air particulate matter concentrations in an urban setting tend to be much lower than those in a rural setting. Also evident is that piles that elevated tend to decrease the air concentrations to nearby receptors. However, the receptor at 0m would have slightly elevated particulates concentrations. While these tend to be very small percentage changes, they could underestimate the particulates lower receptors would be exposed to.

Comparison of Outputs Changing Rural/Urban and Height Inputs ($\mu g\ m^{-3}$)

Percentiles (size/distance)	as Modeled	in Urban Setting	with 10m Height	with 0m Receptor
50/50	5.4	0.6	3.6	6.8
60/40	7.6	0.8	4.8	7.7
70/30	10.7	1.1	6.8	10.8
80/20	19.0	1.9	11.9	19.3
90/10	26.4	2.7	17.8	26.8

All outputs were calculated under the daily management scenario

Appendix D – SCREEN3 Model Runs

The SCREEN3 model was run a total of 65 times to generate the data in this report. Below are the inputs and outputs for each model run. Table D.1 lists all of the common inputs used for all 65 model runs and Tables D.2 through D.7 list all of the uncommon inputs and the resulting outputs for each combination. It is important to note that the discrete distances entered here were calculated by adding the distance from the center of the landfill to the edge and the distance from the edge of the landfill to the receptor. The distance from the center of the landfill to the edge of the landfill was ½ the side length from the Table 2 distribution, and the distance from the edge of the landfill to the receptor was the Table 3 distribution.

Table D.1 – Common Inputs for SCREEN3

Parameter Description	Common Value
Source type	Area
Emission rate (g/s-m^2)	0.000243[1]
Height of storage pile (m)	0[2]
Receptor height (m)	1.75
Urban or Rural	Rural[3]
Search for maximum direction	Yes
Choice of meteorology	Full
Automated distance array	Yes
Minimum distance (m)	0
Maximum distance (m)	1500
Use discrete distances	Yes

[1] Calculated using the workbook (U.S. EPA, 1992).

[2] 10m was selected for the five model runs in Table D.6.

[3] Urban was selected for the five model runs in Table D.7.

Table D.2 – Variable Inputs and Outputs for Whole WMU Runs

Length of Storage Pile (m)	Width of Storage Pile (m)	Distance (m)	Output (μg m^{-3})
518.8	518.8	686.4	13,390

Table D.3 – Variable Inputs and Outputs for Table 6 Runs

Length of Storage Pile (m)	Width of Storage Pile (m)	Distance (m)	Output (μg m^{-3})
82.0	82.0	686.4	1388
23.7	23.7	686.4	159.4
11.4	11.4	686.4	38.0
4.3	4.3	686.4	5.4

Table D.4 – Variable Inputs and Outputs for Table 7 Runs

Length of Storage Pile (m)	Width of Storage Pile (m)	Distance (m)	Output ($\mu g\ m^{-3}$)
11.4	11.4	606.4	38.0
12.9	12.9	720.3	44.9
15.4	15.4	777.5	56.6
20.1	20.1	886.2	78.0
24.1	24.1	975.7	95.9
11.4	11.4	625.4	44.3
12.9	12.9	659.3	51.9
15.4	15.4	716.5	64.3
20.1	20.1	825.2	87.1
24.1	24.1	914.7	105.9
11.4	11.4	564.4	52.5
12.9	12.9	598.3	60.9
15.4	15.4	655.5	74.2
20.1	20.1	764.2	98.1
24.1	24.1	853.7	117.8
11.4	11.4	442.4	78.3
12.9	12.9	476.3	88.4
15.4	15.4	533.5	104.0
20.1	20.1	642.2	129.1
24.1	24.1	731.7	149.1
11.4	11.4	363.4	107.5
12.9	12.9	397.3	118.4
15.4	15.4	454.5	134.6
20.1	20.1	563.2	159.5
24.1	24.1	652.7	178.4

Table D.5 – Variable Inputs and Outputs for Table 8 Runs

Length of Storage Pile (m)	Width of Storage Pile (m)	Distance (m)	Output (µg m^{-3})
4.3	4.3	606.4	5.4
4.9	4.9	720.3	6.5
5.8	5.8	777.5	8.1
7.6	7.6	886.2	11.3
9.1	9.1	975.7	13.9
4.3	4.3	625.4	6.4
4.9	4.9	659.3	7.6
5.8	5.8	716.5	9.2
7.6	7.6	825.2	12.7
9.1	9.1	914.7	15.42
4.3	4.3	564.4	7.6
4.9	4.9	598.3	8.9
5.8	5.8	655.5	10.7
7.6	7.6	764.2	14.3
9.1	9.1	853.7	17.2
4.3	4.3	442.4	11.3
4.9	4.9	476.3	13.0
5.8	5.8	533.5	15.1
7.6	7.6	642.2	19.0
9.1	9.1	731.7	21.9
4.3	4.3	363.4	15.7
4.9	4.9	397.3	17.6
5.8	5.8	454.5	19.7
7.6	7.6	563.2	23.6
9.1	9.1	652.7	26.4

Table D.6 – Variable Inputs and Outputs for Urban Runs

Length of Storage Pile (m)	Width of Storage Pile (m)	Distance (m)	Output (µg m^{-3})
4.3	4.3	606.4	0.6
4.9	4.9	659.3	0.8
5.8	5.8	655.5	1.1
7.6	7.6	642.2	1.9
9.1	9.1	652.7	2.7

Table D.7 – Variable Inputs and Outputs for 10m Height Runs

Length of Storage Pile (m)	Width of Storage Pile (m)	Distance (m)	Output ($\mu g\,m^{-3}$)
4.3	4.3	606.4	3.6
4.9	4.9	659.3	4.8
5.8	5.8	655.5	6.8
7.6	7.6	642.2	11.9
9.1	9.1	652.7	17.8

Table D.8 – Variable Inputs and Outputs for 0m Receptor Runs

Length of Storage Pile (m)	Width of Storage Pile (m)	Distance (m)	Output ($\mu g\,m^{-3}$)
4.3	4.3	606.4	6.8
4.9	4.9	659.3	7.7
5.8	5.8	655.5	10.8
7.6	7.6	642.2	19.3
9.1	9.1	652.7	26.8

Appendix E – Excerpts from the SCREEN3 Manual

The following excerpts selected below have been taken from the SCREEN3 Model User's Guide (U.S. EPA, 1995b). Pages 43-56 provide a technical description of the air modeling equations that are used by SCREEN3.

3. TECHNICAL DESCRIPTION

Most of the techniques used in the SCREEN model are based on assumptions and methods common to other EPA dispersion models. For the sake of brevity, lengthy technical descriptions that are available elsewhere are not duplicated here. This discussion will concentrate on how those methods are incorporated into SCREEN and on describing those techniques that are unique to SCREEN.

3.1 Basic Concepts of Dispersion Modeling

SCREEN uses a Gaussian plume model that incorporates source-related factors and meteorological factors to estimate pollutant concentration from continuous sources. It is assumed that the pollutant does not undergo any chemical reactions, and that no other removal processes, such as wet or dry deposition, act on the plume during its transport from the source. The Gaussian model equations and the interactions of the source-related and meteorological factors are described in Volume II of the ISC user's guide (EPA, 1995b), and in the Workbook of Atmospheric Dispersion Estimates (Turner, 1970).

The basic equation for determining ground-level concentrations under the plume centerline is:

$$
\begin{aligned}
X = Q/(2\pi u_s \sigma_y \sigma_z) \{ & \exp[-\tfrac{1}{2}((z_r-h_e)/\sigma_z)^2] \\
& + \exp[-\tfrac{1}{2}((z_r+h_e)/\sigma_z)^2] \\
& + \sum_{N=1}^{k} [\ \exp[-\tfrac{1}{2}((z_r-h_e-2Nz_i)/\sigma_z)^2] \\
& + \exp[-\tfrac{1}{2}((z_r+h_e-2Nz_i)/\sigma_z)^2] \\
& + \exp[-\tfrac{1}{2}((z_r-h_e+2Nz_i)/\sigma_z)^2] \\
& + \exp[-\tfrac{1}{2}((z_r+h_e+2Nz_i)/\sigma_z)^2]\ ]\ \} \qquad (1)
\end{aligned}
$$

where:

- X = concentration (g/m^3)
- Q = emission rate (g/s)
- π = 3.141593
- u_s = stack height wind speed (m/s)
- σ_y = lateral dispersion parameter (m)
- σ_z = vertical dispersion parameter (m)
- z_r = receptor height above ground (m)
- h_e = plume centerline height (m)
- z_i = mixing height (m)
- k = summation limit for multiple reflections of plume off of the ground and elevated inversion, usually ≤ 4.

Note that for stable conditions and/or mixing heights greater than or equal to 10,000m, unlimited mixing is assumed and the summation term is assumed to be zero.

Equation 1 is used to model the plume impacts from point sources, flare releases, and volume releases in SCREEN. The SCREEN volume source option uses a virtual point source approach, as described in Volume II (Section 1.2.2) of the ISC model user's guide (EPA, 1995b). The user inputs the initial lateral and vertical dimensions of the volume source, as described in Section 2.7 above.

The SCREEN model uses a numerical integration algorithm for modeling impacts from area sources, as described in Volume II (Section 1.2.3) of the ISC model user's guide (EPA, 1995b). The area source is assumed to be a rectangular shape, and the model can be used to estimate concentrations within the area.

3.2 Worst Case Meteorological Conditions

SCREEN examines a range of stability classes and wind speeds to identify the "worst case" meteorological conditions, i.e., the combination of wind speed and stability that results in the maximum ground level concentrations. The wind speed and stability class combinations used by SCREEN are given in Table 2. The 10-meter wind speeds given in Table 2 are adjusted to stack height by SCREEN using the wind profile power law exponents given in Table 3-1 of the screening procedures document. For release heights of less than 10 meters, the wind speeds listed in Table 2 are used without adjustment. For distances greater than 50 km (available with the discrete distance option), SCREEN sets 2 m/s as the lower limit for the 10-meter wind speed to avoid unrealistic transport times. Table 2 includes some cases that may not be considered standard stability class/wind speed combinations, namely E with winds less than 2 m/s, and F with winds greater than 3 m/s. The combinations of E and winds of 1 - 1.5 m/s are often excluded because the algorithm developed by Turner (1964) to determine stability class from routine National Weather Service (NWS) observations excludes cases of E stability for wind speeds less than 4 knots (2 m/s). These combinations are included in SCREEN because they are valid combinations that could appear in a data set using on-site meteorological data with another stability class method. A wind speed of 6 knots (the highest speed for F stability in Turner's scheme) measured at a typical NWS anemometer height of 20 feet (6.1 meters) corresponds to a 10 meter wind speed of 4 m/s under F stability. Therefore the combination of F and 4 m/s has been included.

Table 2. Wind Speed and Stability Class Combinations

Used by the SCREEN Model

Stability Class	10-m Wind Speed (m/s) 1	1.5	2	2.5	3	3.5	4	4.5	5	8	10	15	20
A	*	*	*	*	*								
B	*	*	*	*	*	*	*	*	*				
C	*	*	*	*	*	*	*	*	*	*	*		
D	*	*	*	*	*	*	*	*	*	*	*	*	*
E	*	*	*	*	*	*	*	*	*				
F	*	*	*	*	*	*	*						

The user has three choices of meteorological data to examine. The first choice, which should be used in most applications, is to use "Full Meteorology" which examines all six stability classes (five for urban sources) and their associated wind speeds. Using full meteorology with the automated distance array (described in Section 2), SCREEN prints out the maximum concentration for each distance, and the overall maximum and associated distance. The overall maximum concentration from SCREEN represents the controlling 1-hour value corresponding to the result from Procedures (a) - (c) in Step 4 of Section 4.2. Full meteorology is used instead of the A, C, and E or F subset used by the hand calculations because SCREEN provides maximum concentrations as a function of distance, and stability classes A, C and E or F may not be controlling for all distances. The use of A, C, and E or F may also not give the maximum concentration when building downwash is considered. The second choice is to input a single stability class (1 = A, 2 = B, ..., 6 = F). SCREEN will examine a range of wind speeds for that stability class only. Using this option the user is able to determine the maximum concentrations associated with each of the individual procedures, (a) - (c), in Step 4 of Section 4.2. The third choice is to specify a single stability class and wind speed. The last two choices were originally put into SCREEN to facilitate testing only, but they may be useful if particular meteorological conditions are of concern. However, they are not recommended for routine uses of SCREEN.

The mixing height used in SCREEN for neutral and unstable conditions (classes A-D) is based on an estimate of the mechanically driven mixing height. The mechanical mixing height, z_m (m), is calculated (Randerson, 1984) as

$$z_m = 0.3\ u^*/f \qquad (2)$$

where: u^* = friction velocity (m/s)
f = Coriolis parameter ($9.374 \times 10^{-5}\ s^{-1}$ at 40° latitude)

Using a log-linear profile of the wind speed, and assuming a surface roughness length of about 0.3m, u^* is estimated from the 10-meter wind speed, u_{10}, as

$$u^* = 0.1\ u_{10} \qquad (3)$$

Substituting for u^* in Equation 2 we have

$$z_m = 320\ u_{10}. \qquad (4)$$

The mechanical mixing height is taken to be the minimum daytime mixing height. To be conservative for limited mixing calculations, if the value of z_m from Equation 3 is less than the plume height, h_e, then the mixing height used in calculating the concentration is set equal to $h_e + 1$. For stable conditions, the mixing height is set equal to 10,000m to represent unlimited mixing.

3.3 Plume Rise for Point Sources

The use of the methods of Briggs to estimate plume rise are discussed in detail in Section 1.1.4 of Volume II of the ISC user's guide (EPA, 1995b). These methods are also incorporated in the SCREEN model.

Stack tip downwash is estimated following Briggs (1973, p.4) for all sources except those employing the Schulman-Scire downwash algorithm. Buoyancy flux for non-flare point sources is calculated from

$$F_b = gv_s d_s^2 (T_s - T_a)/(4T_s), \quad (5)$$

which is described in Section 4 of the screening procedures document and is equivalent to Briggs' (1975, p. 63) Equation 12.

Buoyancy flux for flare releases is estimated from

$$F_b = 1.66 \times 10^{-5} \times H, \quad (6)$$

where H is the total heat release rate of the flare (cal/s). This formula was derived from Equation 4.20 of Briggs (1969), assuming T_a = 293K, p = 1205 g/m, c_p = 0.24 cal/gK, and that the sensible heat release rate, Q_H = (0.45) H. The sensible heat rate is based on the assumption that 55 percent of the total heat released is lost due to radiation (Leahey and Davies, 1984). The buoyancy flux for flares is calculated in SCREEN by assuming effective stack parameters of v_s = 20 m/s, T_s = 1,273K, and solving for an effective stack diameter, $d_s = 9.88 \times 10^{-4} (Q_H)^{0.5}$.

The momentum flux, which is used in estimating plume rise for building downwash effects, is calculated from,

$$F_m = v_s^2 d_s^2 T_a/(4T_s). \quad (7)$$

The ISC user's guide (EPA, 1995b) describes the equations used to estimate buoyant plume rise and momentum plume rise for both unstable/neutral and stable conditions. Also described are transitional plume rise and how to estimate the distance to final rise. Final plume rise is used in SCREEN for all cases with the exception of the complex terrain screening procedure and for building downwash effects.

The buoyant line source plume rise formulas that are used for the Schulman-Scire downwash scheme are described in Section 1.1.4.11 of Volume II of the ISC user's guide (EPA, 1995b). These formulas apply to sources where $h_s \leq H_b + 0.5L_b$. For sources subject to downwash but not meeting this criterion, the downwash algorithms of Huber and Snyder (EPA, 1995b) are used, which employ the Briggs plume rise formulas referenced above.

3.4 Dispersion Parameters

The formulas used for calculating vertical (σ_z) and lateral (σ_y) dispersion parameters for rural and urban sites are described in Section 1.1.5 of Volume II of the ISC user's guide (EPA, 1995b).

3.5 Buoyancy Induced Dispersion

Throughout the SCREEN model, with the exception of the Schulman-Scire downwash algorithm, the dispersion parameters, σ_y and σ_z, are adjusted to account for the effects of buoyancy induced dispersion as follows:

$$\sigma_{ye} = (\sigma_y^2 + (\Delta h/3.5)^2)^{0.5} \qquad (8)$$

$$\sigma_{ze} = (\sigma_z^2 + (\Delta h/3.5)^2)^{0.5}$$

where Δh is the distance-dependent plume rise. (Note that for inversion break-up and shoreline fumigation, distances are always beyond the distance to final rise, and therefore Δh = final plume rise).

3.6 Building Downwash

3.6.1 Cavity Recirculation Region

The cavity calculations are a revision of the procedure described in the Regional Workshops on Air Quality Modeling Summary Report, Appendix C (EPA, 1983), and are based largely on results published by Hosker (1984).

If non-zero building dimensions are input to SCREEN for either point or flare releases, then cavity calculations will be made as follows. The cavity height, h_c (m), is estimated based on the following equation from Hosker (1984):

$$h_c = h_b\ (1.0 + 1.6\ \exp\ (-1.3L/h_b)), \qquad (9)$$

where: h_b = building height (m)
L = alongwind dimension of the building (m).

Using the plume height based on momentum rise at two building heights downwind, including stack tip downwash, a critical (i.e., minimum) stack height wind speed is calculated that will just put the plume into the cavity (defined by plume centerline height = cavity height). The critical wind speed is then adjusted from stack height to 10-meter using a power law with an exponent of 0.2 to represent neutral conditions (no attempt is made to differentiate between urban or rural sites or different stability classes). If the critical wind speed (adjusted to 10-meters) is less than or equal to 20 m/s, then a cavity concentration is calculated, otherwise the cavity concentration is assumed to be zero. Concentrations within the cavity, X_c, are estimated by the following approximation (Hosker, 1984):

$$X_c = Q/(1.5\ A_p\ u) \qquad (10)$$

where: Q = emission rate (g/s)
A_p = $H_b \cdot W$ = cross-sectional area of the building normal to the wind (m^2)

W = crosswind dimension of the building (m)
u = wind speed (m/s).

For u, a value of one-half the stack height critical wind speed is used, but not greater than 10 m/s and not less than 1 m/s. Thus, the calculation of X_c is linked to the determination of a critical wind speed. The concentration, X_c, is assumed to be uniform within the cavity.

The cavity length, x_r, measured from the lee side of the building, is estimated by the following (Hosker, 1984):

(1) for short buildings ($L/h_b \le 2$),

$$x_r = \frac{(A)(W)}{1.0 + B(W/h_b)} \quad (11)$$

(2) for long buildings ($L/h_b \ge 2$),

$$x_r = \frac{1.75\ (W)}{1.0 + 0.25(W/h_b)} \quad (12)$$

where:
h_b = building height (m)
L = alongwind building dimension (m)
W = crosswind building dimension (m)
$A = -2.0 + 3.7\ (L/h_b)^{-1/3}$, and
$B = -0.15 + 0.305\ (L/h_b)^{-1/3}$.

The equations above for cavity height, concentration and cavity length are all sensitive to building orientation through the terms L, W and A_p. Therefore, the entire cavity procedure is performed for two orientations, first with the minimum horizontal dimension alongwind and second with the maximum horizontal dimension alongwind. For screening purposes, this is thought to give reasonable bounds on the cavity estimates. The first case will maximize the cavity height, and therefore minimize the critical wind speed. However, the A_p term will also be larger and will tend to reduce concentrations. The highest concentration that potentially effects ambient air should be used as the controlling value for the cavity procedure.

3.6.2 Wake Region

The calculations for the building wake region are based on the ISC model (EPA, 1995b). The wake effects are divided into two regions, one referred to as the "near wake" extending from $3L_b$ to $10L_b$ (L_b is the lesser of the building height, h_b, and maximum projected width), and the other as the "far wake" for distances greater than $10L_b$. For the SCREEN model, the maximum projected width is calculated from the input minimum and maximum horizontal dimensions as $(L^2 + W^2)^{0.5}$. The remainder of the building wake calculations in SCREEN are based on the ISC user's guide (EPA, 1995b).

It should be noted that, unlike the cavity calculation, the comparison of plume height (due to momentum rise at two building heights) to wake height to determine if wake effects apply does not include stack tip downwash. This is done for consistency with the ISC model.

3.7 Fumigation

3.7.1 Inversion Break-up Fumigation

The inversion break-up screening calculations are based on procedures described in the Workbook of Atmospheric Dispersion Estimates (Turner, 1970). The distance to maximum fumigation is based on an estimate of the time required for the mixing layer to develop from the top of the stack to the top of the plume, using Equation 5.5 of Turner (1970):

$$x_{max} = u\, t_m = (u\, p_a\, c_p/R)\ (\Delta\Theta/\Delta z)\ (h_i - h_s)\ [(h_i + h_s)/2] \qquad (13)$$

where:

x_{max} = downwind distance to maximum concentration (m)
t_m = time required for mixing layer to develop from top of stack to top of plume(s)
u = wind speed (2.5 m/s assumed)
p_a = ambient air density (1205 g/m^3 at 20°C)
c_p = specific heat of the air at constant pressure (0.24 cal/gK)
R = net rate of sensible heating of an air column by solar radiation (about 67 $cal/m^2/s$)
$\Delta\Theta/\Delta z$ = vertical potential temperature gradient (assume 0.035 K/m for F stability)
h_i = height of the top of the plume (m) = $h_e + 2\sigma_{ze}$ (h_e is the plume centerline height)
h_s = physical stack height (m).
σ_{ze} = vertical dispersion parameter incorporating buoyancy induced dispersion (m)

The values of u and $\Delta\Theta/\Delta z$ are based on assumed conditions of stability class F and stack height wind speed of 2.5 m/s for the stable layer above the inversion. The value of h_i incorporates the effect of buoyancy induced dispersion on σ_z, however, elevated terrain effects are ignored. The equation above is solved by iteration, starting from an initial guess of x_{max} = 5,000m.

The maximum ground-level concentration due to inversion break-up fumigation, X_f, is calculated from Equation 5.2 of Turner (1970).

$$X_f = Q/[(2\pi)^{0.5}u(\sigma_{ye}+h_e/8)(h_e+2\sigma_{ze})] \quad (14)$$

where Q is the emission rate (g/s), and other terms are defined above. The dispersion parameters, σ_{ye} and σ_{ze}, incorporate the effects of buoyancy induced dispersion. If the distance to the maximum fumigation is less than 2000m, then SCREEN sets $X_f = 0$ since for such short distances the fumigation concentration is not likely to exceed the unstable/limited mixing concentration estimated by the simple terrain screening procedure.

3.7.2 Shoreline Fumigation

For rural sources within 3000m of a large body of water, maximum shoreline fumigation concentrations can be estimated by SCREEN. A stable onshore flow is assumed with stability class F ($\Delta\Theta/\Delta z$ = 0.035 K/m) and stack height wind speed of 2.5 m/s. Similar to the inversion break-up fumigation case, the maximum ground-level shoreline fumigation concentration is assumed to occur where the top of the stable plume intersects the top of the well-mixed thermal internal boundary layer (TIBL).

An evaluation of coastal fumigation models (EPA, 1987b) has shown that the TIBL height as a function of distance inland is well-represented in rural areas with relatively flat terrain by an equation of the form:

$$h_T = A\ [x]^{0.5} \quad (15)$$

where: h_T = height of the TIBL (m)
A = TIBL factor containing physics needed for TIBL parameterization (including heat flux) ($m^{1/2}$)
x = inland distance from shoreline (m).

Studies (e.g. Misra and Onlock, 1982) have shown that the TIBL factor, A, ranges from about 2 to 6. For screening purposes, A is conservatively set equal to 6, since this will minimize the distance to plume/TIBL intersection, and therefore tend to maximize the concentration estimate.

As with the inversion break-up case, the distance to maximum ground-level concentration is determined by iteration. The equation used for the shoreline fumigation case is:

$$x_{max} = [(h_e + 2\sigma_{ze})/6]^2 - x_s \quad (16)$$

where:
x_{max} = downwind distance to maximum concentration (m)
x_s = shortest distance from source to shoreline (m)
h_e = plume centerline height (m)
σ_{ze} = vertical dispersion parameter incorporating buoyancy induced dispersion (m)

Plume height is based on the assumed F stability and 2.5 m/s wind speed, and the dispersion parameter (σ_{ze}) incorporates the effects of buoyancy induced dispersion. If x_{max} is less than 200m, then no shoreline fumigation calculation is made, since the plume may still be influenced by transitional rise and its interaction with the TIBL is more difficult to model.

The maximum ground-level concentration due to shoreline fumigation, X_f, is also calculated from Turner's (1970) Equation 5.2:

$$X_f = Q/[(2\pi)^{0.5}u(\sigma_{ye}+h_e/8)(h_e+2\sigma_{ze})] \quad (14)$$

with σ_{ye} and σ_{ze} incorporating the effects of buoyancy induced dispersion.

Even though the calculation of x_{max} above accounts for the distance from the source to the shoreline in x_s, extra caution should be used in interpreting results as the value of x_s increases. The use of A=6 in Equations 15 and 16 may not be conservative in these cases since there will be an increased chance that the plume will be calculated as being below the TIBL height, and therefore no fumigation concentration estimated. Whereas a smaller value of A could put the plume above the TIBL with a potentially high fumigation concentration. Also, this screening procedure considers only TIBLs that begin formation at the shoreline, and neglects TIBLs that begin to form offshore.

3.8 Complex Terrain 24-hour Screen

The SCREEN model also contains the option to calculate maximum 24-hour concentrations for terrain elevations above stack height. A final plume height and distance to final rise are calculated based on the VALLEY model screening technique (Burt, 1977) assuming conditions of F stability (E for urban) and a stack height wind speed of 2.5 m/s. Stack tip downwash is incorporated in the plume rise calculation.

The user then inputs a terrain height and a distance (m) for the nearest terrain feature likely to experience plume impaction, taking into account complex terrain closer than the distance to final rise. If the plume height is at or below the terrain height for the distance entered, then SCREEN will make a 24-hour average concentration estimate using the VALLEY screening technique. If the terrain is above stack height but below plume centerline height, then SCREEN will make a VALLEY 24-hour estimate (assuming F or E and 2.5 m/s), and also estimate the maximum concentration across a full range of meteorological conditions using simple terrain procedures with terrain "chopped off" at physical stack height, and select the higher estimate. Calculations continue until a terrain height of zero is entered. For the VALLEY model concentration SCREEN will calculate a sector-averaged ground-level concentration with the plume centerline height (h_e) as the larger of 10.0m or the difference between plume height and terrain height. The equation used is

$$X = \frac{2.032\ Q}{\sigma_{ze}\ u\ x} \exp\left[-0.5(h_e/\sigma_{ze})^2\right]. \qquad (17)$$

Note that for screening purposes, concentrations are not attenuated for terrain heights above plume height. The dispersion parameter, σ_{ze}, incorporates the effects of buoyancy induced dispersion (BID). For the simple terrain calculation SCREEN examines concentrations for the full range of meteorological conditions and selects the highest ground level concentration. Plume heights are reduced by the chopped off terrain height for the simple terrain calculation. To adjust the concentrations to 24-hour averages, the VALLEY screening value is multiplied by 0.25, as done in the VALLEY model, and the simple terrain value is multiplied by the 0.4 factor used in Step 5 of Section 4.2.

3.9 Non-regulatory Options

3.9.1 Brode 2 Mixing Height Option

The Brode 2 Mixing Height (Brode, 1991) option calculates a mixing height that is calculated based on the calculated plume height, the anemometer height wind speed and a stability-dependent factor which is compared to a stability-dependent minimum mixing height. The algorithm is expressed as:

$$ZI = MAX\ (ZI_{min},\ HE*(1.0 + ZI_{fact} * U_{10})$$

where ZI_{min} is 300m for A, 100m for B, and 30m for both C and D stabilities, and ZI_{fact} is 0.01 for A, 0.02 for B, 0.03 for C, and 0.04 for D stability. Brode found that the results of using this algorithm appear to provide a fairly consistent level of conservatism relative to the ISCST model.

3.9.2 Variable Anemometer Height Option

The anemometer height is used in adjusting the wind speed to stack height wind speed for cavity calculations based on the following power law function:

```
U0 = U0TEN*(AMAX1(10,HS)/ZREF)**0.20
U1 = U1TEN*(AMAX1(10,HS)/ZREF)**0.20

where:  U0TEN - initial wind speed value set to 20 m/s.
        U1TEN - initial wind speed value set to 1 m/s.
        HS    - stack height
        ZREF  - anemometer height
```

U0TEN is adjusted downward in speed and U1TEN is adjusted upward in speed in an iterative process until the minimum wind speed, UC, that will entrain the plume into a building's cavity is found. The critical wind speed is then adjusted to the anemometer height, using the reverse of the power law above, as follows:

UC10M = UC * (ZREF/AMAX1(10,HS))**0.20

where: UC10M - represents the critical wind speed at anemometer height, ZREF.

The variables HANE and ZREF are used interchangeably.

3.9.3 Schulman-Scire Building Downwash/Cavity Option

A non-regulatory building downwash/cavity algorithm (Schulman and Scire,1993) has been added as a non-regulatory option. This option is based on the diffusing plume approach with fractional capture of the plume by the near-wake recirculation cavity.

Extensive parameterization is used to define a building length scale, roof recirculation cavity, maximum height of the roof cavity, and the length of the downwind recirculation cavity (as measured from the lee face of the building).

A building length scale for flow and diffusion is defined as:

R = BS exp(2/3) * BL exp(1/3)

where: BS is the smaller of the building height and projected width for the minimum side orientation
BL is the larger of the building height and projected width for the maximum side orientation.

The length of the roof recirculation cavity is estimated as:

LC = 0.9 * R

The roof cavity will reattach to the roof if LC < L where L is the downwind length of the roof.

The maximum height of the roof cavity is defined as:

HC = 0.22 * R   at x = 0.5 * R

where x is the downwind distance.

The program uses two algorithms to determine the height and width of the downwind recirculation cavity or near-wake. If the roof cavity reattaches to the roof, the height and width are:

HR = H where H is the building height

$WR = W$ where W is the projected width normal to the wind.

If the roof cavity does not reattach, the height and width are:

$$HR = H + HC$$
$$WR = 0.6 * H + 1.1*W$$

and measured from the lee face of the building.

The length of the recirculation region is calculated using the formula:

$$LR = 1.8W/[(L/H)^{0.3} * (1.0 + 0.24W/H)]$$

with the restriction that L/H is set equal to 0.3 if $L/H < 0.3$, and L/H is set equal to 3.0 if $L/H > 3.0$.

The ground level concentration in the recirculation region is calculated assuming the mass fraction of the plume, below HR at the downwind end of the region, is captured into the region. The

calculation assumes a Gaussian distribution of the vertical mass of the plume at that point using the following formula:

$$\sigma_z = 0.21R^{0.25}\ x^{0.75}$$

The cavity concentration, C, is then calculated as a fraction of the plume content using the following empirical formula:

$$C = f_c * B_0\ Q/(B_0 w_0 A_0 + u_H s^2)$$

where: f_c is the mass fraction of the plume captured in the recirculation region
B_0 is an empirical constant approximately equal to 16
w_0 is the stack exit speed
A_0 is the stack exit face area
u_H is the upwind wind speed at roof level
s^2 is the "stretched string" distance between the stack base and the receptor.

The position of the stack on the roof is taken into consideration. A ratio is calculated based on the distance of the stack from a centerline of the building perpendicular to the wind flow for each of two orientations divided by the along wind flow length of the building. Below is an example where the along wind flow length is HW and the distance of the stack from the centerline is "x"; producing a ratio of .4. Note that the ratio is always a positive number. Ratios greater than .5 indicate that the stack is not on the roof.

```
v------------ HW --------------v
+--------------.---------------+
```

```
                         |                 .                 |
(x/HW = .4)-->           |   S             :                 |          HL
                         |   ^-----x------^                  |
                         |                 .                 |
                         +-----------------.-----------------+
                        .5                 0                .5
```

```
                              HL
                       +-------.-------+
                       |       .       |
(x/HL = .15)--->       |       .  S    |
                       |       .       |
                       |       .       |
                       |       .       |          HW
                       |       .       |
                       |       .       |
                       |       .       |
                       |       .       |
                       +-------.-------+
                      .5       0      .5
```