Background Information for proposed CEAC woodsmoke ordinance of 2007

Robert Clear, Draft: December 17, 2007

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Background and Introduction

The city of Berkeley banned non-EPA certified wood burning appliances in new construction in 2001. The purpose of the ban was to help the city maintain ambient air quality, particularly with regard to fine particulate matter (PM). However, the city has a large stock of non-EPA units in the existing building stock, and the Community Environmental Advisory Commission (CEAC) has continued to receive complaints of local air quality problems from residents who are near neighbors to an operating wood burning appliance.

Residents who were concerned that their health problems were directly connected to their exposure to wood smoke came to CEAC because they had unable to get the operator of the wood burning appliance to stop or limit its use. Of particular concern to CEAC was that their complaints were not limited to days when ambient particulate levels were high. The issue instead appeared to primarily one of proximity, and local conditions.

There is a precedent for regulation of purely local problems in the regulation of toxic hot spots, and cigarette smoke. In examining the issue the CEAC determined that it would be a practical impossibility to measure the PM levels on a case by case basis. The alternative was to consider computer simulations to see if it was possible to determine if there were conditions where it could reasonably be expected that operation of a wood burning appliance would cause a health hazard.

The author of this report volunteered to run the computer simulations, and the Bay Area Air Quality Management District (BAAQMD) helped CEAC obtain a copy of the Screen3 computer program. The Screen3 program computes the concentration of pollutants in a plume emitted from a stack (chimney) from the characteristics of the plume, given a information on the surrounding geometry and wind conditions. Brian Bateman, and Scott Lutz from the BAAQMD, graciously provided information on some of the questions the author had about running the Screen3 model. Information on woodburning was primarily derived from internet research. Any errors in running the Screen3 program or interpreting the information on woodburning are the responsibility of the author.

This document describes the results of the simulations, and the criteria used to evaluate the results from the output of the Screen3 model. It also documents the assumptions and inputs used in the Screen3 model. The author has attempted to reference most of the input values, however not all the documents used could be traced back to their original sources. Internet references are given as URLs, and may not list a date.

Criteria for Evaluation

The Screen3 program calculates the concentration of the target pollutant as a function of the distance from the source. To determine whether wood smoke was a hazard we compared the computed concentrations to ambient air quality standards. The California Air Resources Board (ARB) and the Federal Environmental Protection Agency (EPA) have produced air quality standards for PM of 10 microns or less (PM10) and 2.5 microns or less (PM2.5) in size. The standards that are relevant to a local intermittant exposure, such as is likely to be caused by operation of a residential wood burning appliance, regulate the average concentration in ambient air over a period of 24 hours. The federal and state standards for particulate matter are listed in the table below:

Table 1: Particulate matter standards for the average exposure level in μg/cubic meter of air over a 24 hour period

Particulate matter	California	Federal (2005)	Federal (2006+)
PM10	50	150	150
PM2.5	none	65	35

Both the PM10 and PM2.5 standards are potentially relevant for wood smoke, as most wood smoke is generally reported to be primarily in the sum-micron range, with an estimated 90% of the particles being less than 1 micron in size.[BI??, DI95, KA84, KO06, TE05] The two most stringent standards are the California PM10 standard (50 $\mu g/m^3$) and the most recent Federal PM2.5 standard (35 $\mu g/m^3$). Since our analysis is concerned with local effects the ambient levels need to be subtracted from these levels to get the allowed exposure from the local source. The average particulate levels in the San Francisco Bay Area area are 27 $\mu g/m^3$ for PM10, and 13 $\mu g/m^3$ for PM2.5.[ARB05] The limited amount of data available specifically for Berkeley is consistent with these values.[EN02] When these ambient levels are subtracted from the regulatory levels the resultant average allowed exposure levels are 23 $\mu g/m^3$ for PM10, and 22 $\mu g/m^3$ for PM2.5. Since most wood smoke particles are below 2.5 microns in size, these standards are approximately the same.

Averaged over a 24 hour period, the above levels equal a total exposure of 23 - 24 $\mu g/m^3$ (24 = 22/0.9) times 24 hours which rounds up to 600 μg-hours/m^3. Any exposure in terms of time and air concentration that exceeds this level is in violation of the air quality standards, and is presumably a health hazard. The Screen3 runs return values for the expected maximum concentration over a one hour period. We were told by technical experts at BAAQMD that the average over a 24 hour period could be as low as 40% of the one hour values returned by the program. The Screen3 program should therefore only slightly overestimate the exposure for exposure durations of two to three hours, and will somewhat underestimate the exposure for durations of less than an hour. Because Berkeley has a mild climate, we expect that wood stove or fireplace operation to typically last no more than a few hours at a time, and we therefore have assumed that we can directly use the Screen3 values to determine the length of time needed to exceed the target level of 600 μg-hours/m^3. The Screen3 results are therefore reported in terms of the hours to exceed the 600 μg-hours/m^3 target level.

Assumptions and inputs used in Screen3 runs

The Screen3 program requires input information on the physical and emission characteristics of the source, the local terrain conditions, and the meteorlogical conditions. The output of the program is the concentration of the pollutant as a function of distance.

Calculations were made for four general types of wood burning appliances: a standard fireplace, a fireplace with glass doors to reduce excess air, a non-EPA compliant wood stove, and an EPA compliant wood stove or fireplace insert. Several runs were made with different chimney diameters and heights, efficiencies, ambient air temperatures, and excess air, to check the sensitivity of the results to changes in the input parameters. The runs were also run for a range of receptor heights and terrain elevations to determine if problems might be more severe in some areas than others.

The input values for the Screen3 runs performed for this analysis are listed in the tables below, and a description of the input values follows the tables. When an input value, such as the temperature of the flue gas, depends upon other variables, the assumptions and input variables for the other variables are also given. Parameters that are actually inputs to the Screen3 model are listed as input parameters. Parameters that were used to compute input values for the Screen3 model are listed as auxillary parameters.

The following variables: source type, mixing height, and anemometer height, were fixed for all runs, and are not listed in the tables. All the runs listed here also used the “downwash” option. One “fireplace” run was performed with both the “urban” and “rural” options, while all the rest of the runs were performed with the “rural” option. Only the data from the rural option are included in the summary data analysis. The other data is described separately in the results section. Input values are listed in metric units: grams/second for the particulate emission rate, meters for building and chimney dimensions, and degrees Kelvin for temperatures. In the first four tables (one for each wood burning appliance type) the meteorological input variable was set to the default “full” value. A final set of runs was performed on the first entry in the fireplace table with explicit values of wind speed and “stability” class conditions. Table 5 lists meteorological conditions studied

Table 1: Fireplaces

table 1 part a.

emission rate	0.0168	0.0168	0.0168	0.0168	0.0168
stack height	4.1	6.1	6.1	8.1	8.1
stack diameter	0.2	0.2	0.2	0.2	0.2
exhaust velocity	3.7	3.7	3.7	3.7	3.7
exit temperature	396	393	392	388	384
air temperature	283	283	283	283	283
building height	3.5	5.2	5.5	7.2	7.5
width	8	8	8	8	8
length	12.5	12.5	12.5	12.5	12.5

table 1 part b.

emission rate	0.0168	0.0168	0.0168	0.0433	0.0122
stack height	4.9	6.7	6.7	6.7	6.7
stack diameter	0.2	0.2	0.2	0.3	0.2
exhaust velocity	3.7	3.6	3.6	4.2	3.6
exit temperature	396	389	389	395	389
air temperature	283	283	283	283	283
building height	4.3	6.1	6.1	6.1	6.1
width	8	10	8	8	8
length	12.5	10	12.5	12.5	12.5

table 1 part c.

emission rate	0.0168	0.0168	0.0168	0.0433
stack height	6.7	6.7	9.1	9.1
stack diameter	0.2	0.2	0.2	0.3
exhaust velocity	3.6	3.9	3.5	4.1
exit temperature	389	423	380	388
air temperature	278	283	283	283
building height	6.1	6.1	8.5	8.5
width	8	8	8	8
length	12.5	12.5	12.5	12.5

Table 2: Fireplaces with glass doors

table 2 part a.

emission rate	0.0122	0.0122	0.0122	0.0122	0.0122
stack height	4.1	6.1	8.1	6.1	8.1
stack diameter	0.2	0.2	0.2	0.2	0.2
exhaust velocity	1.6	1.5	1.5	1.6	1.6
exit temperature	577	523	474	528	485
air temperature	283	283	283	283	283

building height	3.5	5.5	7.5	5.2	7.2
width	8	8	8	8	8
length	12.5	12.5	12.5	12.5	12.5

table 2 part b.

emission rate	0.0122	0.0122	0.0313	0.0122	0.0313
stack height	6.7	4.9	6.7	9.1	9.1
stack diameter	0.2	0.2	0.3	0.2	0.3
exhaust velocity	1.5	1.6	1.8	1.5	1.7
exit temperature	507	556	558	453	513
air temperature	283	283	283	283	283
building height	6.1	4.3	6.1	8.5	8.5
width	8	8	8	8	8
length	12.5	12.5	12.5	12.5	12.5

table 2 part c.

emission rate	0.0168	0.0122	0.0122
stack height	6.7	6.7	6.7
stack diameter	0.2	0.2	0.2
exhaust velocity	1.5	1.5	1.7
exit temperature	507	502	553
air temperature	283	278	283
building height	6.1	6.1	6.1
width	8	8	8
length	12.5	12.5	12.5

Table 3: Non-EPA compliant woodstoves

emission rate	0.0104	0.0104	0.0104	0.0104	0.0104
stack height	4.1	6.1	8.1	6.1	8.1
stack diameter	0.15	0.15	0.15	0.15	0.15
exhaust velocity	1.2	1.2	1.2	1.2	1.2
exit temperature	603	499	429	499	429
air temperature	283	283	283	283	283
building height	3.5	5.5	7.5	5.2	7.2
width	8	8	8	8	8
length	12.5	12.5	12.5	12.5	12.5

Table 4: EPA compliant woodstoves or fireplace inserts

table 4 part a

emission rate	0.0018	0.0018	0.0018	0.0018	0.0018
stack height	4.1	6.1	8.1	4.4	6.1

stack diameter	0.15	0.15	0.15	0.15	0.15
exhaust velocity	0.9	0.9	0.9	0.9	0.9
exit temperature	498	422	371	487	426
air temperature	283	283	283	283	283
building height	3.5	5.5	7.5	3.5	5.2
width	8	8	8	8	8
length	12.5	12.5	12.5	12.5	12.5

table 4 part b

emission rate	0.0018	0.0018	0.0029	0.0018	0.0029
stack height	6.7	4.9	6.7	9.1	9.1
stack diameter	0.15	0.15	0.2	0.15	0.2
exhaust velocity	0.9	0.9	0.8	0.9	0.8
exit temperature	404	466	431	352	374
air temperature	283	283	283	283	283
building height	6.1	4.3	6.1	8.5	8.5
width	8	8	8	8	8
length	12.5	12.5	12.5	12.5	12.5

table 4 part c

emission rate	0.0018	0.0018
stack height	6.7	6.7
stack diameter	0.15	0.15
exhaust velocity	0.9	1.2
exit temperature	398	469
air temperature	278	283
building height	6.1	6.1
width	8	8
length	12.5	12.5

Table 5: Meteorological runs

Stability class	Wind speeds (meters/second)			
A	1	2.5		
B	1	2.5	5	
C	1	2.5	5	10
D	1	2.5	5	10
E	1	2.5	5	
F	1	2.5		

Local terrain conditions:

The Screen3 program requires values for the six following terrain inputs:

	Variable	Value(s)
1)	Terrain input	Simple
2)	Area type	Rural
3)	Downwash	Yes
4)	Terrain height	0 - 8 meters in 2 meter increments
5)	Receptor height	2, 4 and 6 meters above terrain height
6)	Receptor distance	minimum cavity value to 100 meters

Terrain input:

Screen3 has two terrain input options: simple or complex. The simple option is for cases where the terrain is lower than the stack height, while the complex option allows the user to assess situations where the terrain elevations exceed the stack height. One test set of conditions was run with both the simple and complex options. At a 1:1 vertical rise to horizontal ratio, the concentration at 7 meters exceeded by a factor of two the maximum value for the simple case, but the concentration dropped to essentially zero one meter farther away. For slopes of 1:2 or less the high concentrations covered a larger area, but were also farther away, and were therefore lower than values for the simple case near stack height but closer, or within the downwash zone. The 1:1 slope calculation is a very extreme case, and gives extremely position dependent results, while the less extreme slopes are actually less of a concern than the simple case with downwash. Further calculations were therefore confined to the simple test case.

Mr. Bateman of BAAQMD confirmed that the Screen3 treatment of terrain was very simplified, and indicated that it should be conservative.

Area:

The Screen3 model has two choices: urban or rural. Although Berkeley would commonly be thought of as urban, the definitions for the Screen3 model are not related to just the population. BAAQMD indicated that the rural option was more appropriate. All but run was performed with the rural option. A check case was run with the urban option to provide information on the sensitivity of the results to this input parameter.

Downwash:

Screen3 allows calculations for isolated stacks (no downwash) or stacks located on a building, which can create a wake and downwash effect. Residential fireplaces and chimneys were assumed to always be associated with a building, so downwash was calculated for all cases. Two test cases were run with and without downwash as a check. The no downwash option generally gives much lower particulate concentrations.

Mr. Bateman confirmed that downwash is appropriate for chimneys, but noted that the standard EPA routine is very conservative. He therefore suggested comparing the results against the non-regulatory downwash option in the Screen3 model.

The Screen3 model has a regulatory downwash option, and two non-regulatory options. The non-regulatory options allow the user to place the stack at an arbitrary location on the building. Chimney locations in Berkeley will vary. Edge locations were tested for a standard burn rate reference condition. The PM10 concentrations using the non-regulatory option were considerably higher than for the regulatory option, but still considerably less than the concentrations outside the downwash zone. The general summary of the results used the regulatory downwash option.

receptor height (meters)
Receptor height is defined as the height above the local ground level. We assumed that the subject population of interest is the population in nearby buildings. Three heights were examined, 2, 4 and 6 meters above the local ground level, to represent subjects in a first or second story in a building adjacent to the chimney.

terrain height (meters)
Berekely terrain varies from flat to hilly. For hilly slopes the elevation increases as distance from the stack increases, however particulate concentrations also tend to decrease as distance from the stack increases. The simple terrain option constrains the terrain elevations to less than the stack height, and the terrain height input was varied from 0 meters to the nearest even integer below the stack height (0 to 8 meters overall). Variations in terrain height and receptor heights give similar variations in the calculated particulate concentrations, so the effective rise is approximately 14 meters. In the calculations we assumed slopes of 45° or less, so the calculations should be reasonable for distances up to 14 meters. The use of the complex terrain height option and higher terrain elevations would be only

be applicable to farther distances, and presumably lower particulate concentrations, and therefore was not pursued.

Scott Lutz of BAAQMD suggesting using actual terrain data for Berkeley, but the analysis was not meant to be specific to any one site. The idea is to cover a range of conditions that are representative of what might be found in the city.

receptor distance (meters)
Screen3 is normally used to compute pollutant impacts up to kilometers in distance from tall stacks. As stated earlier, our interest in the fireplaces and chimneys calculations is with regards to the nearby local effects. A maximum calculation distance of 100 meters (328 feet) was found to be sufficient to establish the general trend of the pollution levels, and to cover all the nearest neighbors. The minimum distance was established as the maximum of the edge of the cavity distance determined by Screen3, or the terrain height. Calculations were done in sufficiently close increments to show a reasonably smooth shape for the pollutant concentrations when plotted versus distance.

Physical Characteristics of the Source:

There were six input variables that described the physical characteristics of the source:

Variable	Value
1) Source type	Point
2) stack height (meters)	4.1 to 9.1
3) stack diameter (meters)	0.15, 0.2, or 0.3
4) *building height (meters)	3.5 to 8.5
5) *building width (meters)	8 or 10
6) *building length (meters)	12.5 or 10

* These entries only apply to calculations with the downwash option (described previously)

Source type

Source type can be point, flare, area, or volume. The flare option appears to be for an open flame, and is not appropriate for a chimney. The point, area, and volume options are for sources that can be approximated as stated. Mr. Bateman of BAAQMD confirmed that the point option is the appropriate option for the chimney stack.

stack height (meters)

Chimney heights are required to be a minimum of two feet (0.6 meters) above highest roof surface within 10 feet of the chimney.[KE??, HC??] Stack height was generally set to the minimum 2 feet (0.6 meters) above the roof height, however calculations were also performed with a chimney height that was 3 feet (0.9 meters) above the roof height.

stack diameter (meters)

Chimney sizes for modern wood stoves were found on an internet reference and were listed as being from 6 to 8 inches (0.15 to 0.2 meters) in diameter.[IN??] Chimney sizes for fireplaces were listed as being from 8 inches (0.2 meters) for a small fireplace to 12 inches (0.3 meters) for a large fireplace. The two small sizes (0.15 and 0.2 meters) were used for low burn rate calculations, while the two larger sizes (0.2 and 0.3 meters) were used for high burn rate calculations.

building height (meters)

The heights used were designed to span the likely range of single family dwellings in Berkeley. The lowest was a low crawl space or slab on grade, relatively flat pitched roof, one story house of approximately 11.5 feet (3.5 meters). The tallest was a two story house of 28 feet (8.5 meters).

building width (meters) and building length (meters)

The building was assumed to cover 100 square meters in either a square format (10 x 10 meters) or rectangular format (8 x 12.5 meters).

Meterological Conditions:

The Screen3 program has four variables to describe meterological conditions:

Variable	Value
mixing ht.	default
anemometer ht.	default
meterology	full or explicit speed and stability
Ambient air temperature (°K)	283 (278)

Mixing height

The mixing height is the height above the ground within which the plume is confined by inversion conditions and the exhaust speed of the plume. The mixing height is calculated within the program according to one of two options: a default calculation described in section 3.2 of the manual, or a non-regulatory but "conservative" method developed by Brode described in section 3.9.1. BAAQMD indicated that the default calculation would be appropriate for our purposes. All runs using the default mixing height.

Anemometer height

Screen3 adjusts wind speeds from the anemometer height to the stack height. The default anemometer height option is 10 meters, but the user is allowed to enter an explicit height for cavity calculations. BAAQMD again recommended using the default option.

Meterology

There are three choices: full, explicit entry of a stability class with Screen3 examining all wind speeds that are relevant to that class, or explicit entry of a stability class and wind speed. The "full" meteorology choice runs with all stability class, wind speed combinations relevant to the land type. The manual recommends the first choice in most cases, and notes that the other two choices were originally included for "testing" (debugging?) purposes, and were retained in case the user was interested in particular meteorological conditions. Scott Lutz has suggested that we could look at the University of California's meteorological data. However the purpose of our analysis was to determine what conditions could create a health hazard, so the only real point of examining this data would be to eliminate weather conditions that do not occur in the area. It was assumed that these would be the most extreme conditions, which are unlikely to give particularly high pollution levels anyway, so this option was not explored further.

When Screen3 is run with the default “full” value it chooses the meterological conditions which give the highest particulate concentrations expected. Our initial runs used the default value. After we determined that operation of a standard fireplace or wood stove could lead to particulate concentrations that exceeded our target value, we reran a set of the conditions over the full range of stability classes and wind speeds to determine how sensitive the results were to the meteorolgical conditions.

Ambient air temperature (°K)
It was assumed that fireplaces and stoves are most likely to be used in cold or cool weather. In general, colder weather gives lower Screen3 particulate concentration estimates, because plume buoyancy and lift is higher. The bulk of the Screen3 cases were therefore run at 50 °F (283 °K) as representative of a cool, but relatively warm condition. Several test runs were made at 41 °F (278 °K) as a check.

The remaining three Screen3 input parameters vary in value with stack height and diameter, ambient temperature, and a number of other variables which described are below as auxiillary input parameters:

Source emission characteristics:

Variable	Value
emission rate (grams/second)	computed
flow rate (m^3/sec)	computed
flue temp. (°K)	computed

Auxillary Input Parameters	**Values**
burn rate (dry kg)	3, 3.5 & 9
PM10 in g/kg	2.1 to 17.3
combustion air required l/kg (wet)	4250
flue gas/wet wood l/kg (no excess air)	5000
excess air	0.5, 0.6, 3, 9.4, & 15
moisture content of wood (%)	20%
heat of vaporization (%)	11%
BTU/kg - dry wood	18900
flue conductivity (BTU/m^2-°C-hr)	13.65
height of flue above ground (m)	1.7
heat capacity of flue gas (BTU/l-°C)	0.00114
house temperature (°K)	293
efficiency	0.1, 0.3, 0.4, 0.5, 0.6, & 0.7

The information available on the three input parameters was very general, and it was not possible to relate to any specific set of conditions. The inputs were therefore computed from the auxillary inputs, and checked against the general information to ensure that it was reasonable.

emission rate (grams/second)

The Bay Area Air Quality Management District (BAAQMD) estimates particulate emission rates for PM10 for an uncertified woodstove or insert as 60 grams/hour (0.017 grams/second).[BA??] An average of the rated emission rates for 15 stoves sold in Berkeley in 1999 was 3.4 grams/hour (0.0009 grams/sec). The emission rates should depend upon the rate at which wood is being burned. The values for the woodstoves are based on a standardized test procedure (method 28) which averages burn rates upto the stove’s rated maximum. Based on a calculation from the published procedure, the rated average burn rate for the wood stoves sold in Berkeley was 1.7 kg (dry weight) of wood per hour. Emission rates used in the Screen3 runs were based on burn rates and estimates of emissions/kg of wet wood. Since the burn rates used in the testing procedures was low compared to estimated residential burn rates, the computed values ranged considerably above the listed values here. Computed particulate rates for standard fireplaces ranged from 40 to 155 grams/hour, while the rates for EPA certified woodstoves ranged from 6 to 10 grams/hour.

flow rate (m^3/sec)
Houck et. al. [HO02] describe air flow rates for fireplaces as being in the range of "typically a few hundred cubic feet per minute" (200 cubic feet per minute (cfm) = 0.093 cubic meters/second). Woodheat.org explicitly lists the range of an open fire as being from 200 to 600 cfm (0.093 to 0.283 m^3/sec).[WO??] The use of glass doors is claimed to significantly reduce the flow rate to the 50 to 150 cfm range.[WO??]. A test of the propensity of fireplaces with glass doors to spill exhaust into the house measured exhaust rates of 100 cfm [OR89], which is consistent with the values listed by Woodheat.org. The flow rates for EPA certified woodstoves was given as 10 to 30 cfm (0.005 to 0.014 m^3/sec) by Houck et. al. [HO02]. Woodheat.org lists EPA certified stoves as 15-30 cfm.[WO??] Hayden claims a typical fireplace uses 1500 percent excess air, and lists the air requirement for wood with a 17% moisture requirement as being about 4250 liters/kg-wet wood.[HA??] Woodstoves were listed as being about 100% excess air. Flue gas volumes for Screen3 were based on Hayden's 1500 % excess estimate for fireplaces. For non-EPA woodstoves or glass door inserts, and EPA certified woodstoves the excess air was assumed to scale by 1/5 and 1/30 to match the air requirements listed as typical for these appliances. Calculated room air flow rates ranged from 175 - 450 cfm for open fireplaces, 44 - 113 cfm for non-EPA woodstoves or fireplaces with glass doors, and 14 -23 cfm for EPA certified woodstoves, and thus appear to be slightly low to about the middle of the range.

All of the above air volume flow rates appear to be flow rates for the air in the room, at room temperature and pressure. The fire in the woodstove or fireplace heats the air, which causes it to expand. In addition, more gas is released in combustion than is consumed from the air, so flue gas flow rates, as measured in terms of their actual volume, are larger than room air flow rates. BAAQMD confirmed that Screen3 expects the actual flow rate from the stack as the input. Flue gas volume flow rates are calculated from the excess air and burn rate inputs by scaling the room air volumes by the ratio of the flue gas temperature (in °K) to an assumed room air temperature (293 °K = 68°F). Let B = the wet wood burn rate in kg/hr, A =

the combustion air requirement per kg of wet wood (≈ 4250 liters/kg), E = the excess air consumption, and C = the excess of combustion gas volume versus the oxygen consumption per kg (=5000 - 4250 = 750 l/kg wet wood). The flue gas rate, F was calculated from the formula:

F = B x (A x (E + 1) + C

The Screen3 input stack gas velocities are 3.6 - 4.1 m/sec for open fireplaces, 1.5 - 1.7 m/sec for fireplaces with glass doors, 1.2 m/sec for non-compliant woodstoves, and 0.8 - 1.2 m/sec for EPA compliant woodstoves. The range in above velocities appears much smaller than the range in combustion air listed earlier because there is a range in chimney diameters. The range in volume flows; 240 - 625 cfm, 100 - 265 cfm, and 32 -56 cfm for the three choices respectively can be seen to be similar to the range in combustion air demands.

flue temp. (°K)
Woodheat.org [WO??] lists normal flue temperatures as being in the 200 - 1000 °F range (366 - 813 °K). Type A vents used for gas are limited to 1000 °F. A burn rate test gave temperatures in the 100°C to 300 °C range (373 to 573 °K) [OR89] for a wood stove with glass doors. Kerr heating products [KE??] provides a table of flue draft pressures versus chimney height and flue gas temperature, with the temperatures ranging from 340 °K, to 620 °K. They recommend that minimum temperatures not drop below 167 °F (348 °K) as this causes condensation of water and can lead to the formation of sulfuric acid condensate on the flue. The flue gas temperature goal of a modern EPA compliant wood stove is in the 150 to 200 °C (423 to 473 °K) range as this is the temperature below which creosote condenses. [SC99] Flue temperatures were estimated from a heat balance equation and ranged from 174 °F to 544 °F (352 to 558 °K). The one low temperature was for the low burn rate, and a high efficiency woodstove with a tall chimney, and consequently high conductive heat losses. A lower efficiency would lead to a more reasonable flue temperature in this case.

The heat that was lost to conductive flue losses and sensible heat of the flue gases, Q_f, was estimated from the equation:

$Q_f = Q_{in} \times (1 - v_f - \mathrm{eff}) - Q_{ra}$, where Q_{in} is the heat input from burning wood, v_f is the fraction of the input heat lost to vaporizing water (assumed to be 11%), eff is the overall efficiency of the fireplace or woodstove (assumed to range from 0.1 to 0.7), and Q_{ra} is the heat loss to heating the combustion air from outside temperature to house temperature.

The temperature of the flue gas at the bottom of the flue minus the room temperature, T_f(bottom), is then:

$T_f(\text{bottom}) = Q_f/(\text{FR} \times \text{HC})$,

where FR is the flow rate of flue gas in liters at 288.16 °K and and 1 atmosphere pressure, and HC = 0.00114 BTU/l-°C (at STP) is the heat capacity of the flue gas.

The temperature at the top of the stack was calculated by approximating the density of the flue gas as a constant over the temperature range in the stack. This approximation leads to an exponential temperature distribution with the form:

$T_f(\text{top}) = T_f(\text{bottom}) \times \exp^{\{-4U \times ht/(HC \times f(T) \times FR \times D)\}}$

where ht is the height of the flue pipe, f(T) is the ratio of the flue gas temperature (in °K) to the reference temperature (288.16 °K), and D is the diameter of the flue pipe.

Data on the auxillary parameters was compiled from internet and reference sources.

burn rate (dry kg)
Houck states that the average burn rate (dry weight) is 5.6 kg/hour, with a standard deviation of 3.2 kg/hour.[HO01] The median and mode are lower than the mean weight, and indicate that the distribution is skewed. A burn rate of 3 kg/hour was listed as typical for a small fireplace. For the Screen3 runs I used a slightly larger value of 3.5 kg/hour for a small fireplace to get the air flow rate closer to what was reported in the literature at 15x excess air. I rounded the mean plus one standard deviations ≈ 9 kg/hr for a large fireplace. Specification sheets (Lopi,

Regency and Fireplace Extraordinaire) for woodstoves and inserts list minimum and average heat input rates which when divided by the average heat content of dry wood give burn rates of 3 and 5 kg/hour. The maximum heat input for woodstoves of 6 kg/hour is probably not likely to be used in the city of Berkeley, because of its mild climate.

PM10 in g/kg
The EPA estimate for the ratio of particulate emissions per kg of dry wood burned is 17.3 g/kg.[EPA93] Houck and Tiegs state that a more recent test gave 12.5 g/kg.[HO98] We used the 17.3 g/kg value as the default value for an open fireplace, and the 12.5 g/kg value as the default for a fireplace with a glass door or non-compliant woodstove. One test run was made to check that the particulate values scale with release rate.

The EPA uses method 28 to determine particulate release ratings for woodstoves.[EPA00] The ratings are based on an average over a number of different burn rates. For the catalog data we compiled (Lopi, Regency and Fireplace Extraordinaire), the average emission rate was 3.4 g/hr, and the calculated average burn rate for the EPA test was 1.66 kg/hr. The average computed emission factor was 2.1 g/kg.

combustion air required l/kg (wet)
Hayden lists 4250 liters as the amount of air required to combust one kg of wood with a moisture content of 17%.[HA94] A study by the National Renewable Energy Laboratory lists the composition of a christmas tree as approximately $C_1H_{1.3}O_{0.5}$, plus 5.2% alkali ash.[TM95] This leads to an estimate of 4120 liters of air to combust wood with a 20% moisture content, and 4270 liters to combust wood with a 17% moisture content. Ash contents of a number of other woods appeared smaller, which would lead to higher air requirements. The value of 4250 liters was used in the Screen3 runs, although we also assumed 20 % moisture.

flue gas l/wet kg (no excess air)
Calculations based on wood composition lead to an estimate of 5000 liters of total flue gases: CO_2 + H_2O + N_2, per kg of wet wood.[TM95]

excess air
Excess air for a fireplace is listed as 15 by Hayden.[HA94] Calculations with this excess air quantity and the wood burn rates previously described gives

air flow rates from 180 to 450 cfm, which ranges from slightly lower than the low air flow rates listed for regular fireplaces to the middle of the range (see flow rates above). Air flow rates for glass doors are listed as being 4 times lower, which leads to an excess air rate of 3 (excess air = (15 + 1)/4 - 1).[WO??] Similarly, excess air rates of 0.5 to 0.6 for wood stoves lead to air flow rates in the middle of the range normally cited.

moisture content of wood (%)
The 20% moisture value was listed in a number of places as a typical value for for well seasoned wood[HO01]

heat of vaporization (%)
Buckley notes that a heat of vaporization of water loss of 11% is a good estimate for a wide variety of woods.[BU96] The value is consistent with calculations based on wood composition (see “combustion air required” section.

BTU/kg - dry wood
The value of 18900 BTU/kg (2.0 x 10^7 joules/kg) is from Houck.[HO01] Similar values were listed in a number of other references.

flue conductivity
The value of 13.65 BTU/m^2-°C-hr (4 watts/m^2-°C) is the mid-range value reported by ORTECH international in their laboratory fireplace tests.[OR89] The maximum value they list is basically a bare flue. The mid-range value has some shielding by masonry or brick.

height of flue above ground (m)
Based on an assumed 2 feet from ground to floor, and 3 feet from floor to flue, for approximately 1.7 meters overall.

heat capacity of flue gas
The heat capacity of air per unit weight varies by less than 5% over the temperature range of 100 to 1000°C.[CRC63] The heat capacity per liter of air at STP conditions is 0.00114 BTU/l-°C (1.21 joules/l/°C)

house temperature (°K)
The house temperature was set to 68 °F (293 °K). This is the low end of the comfort range.

efficiency

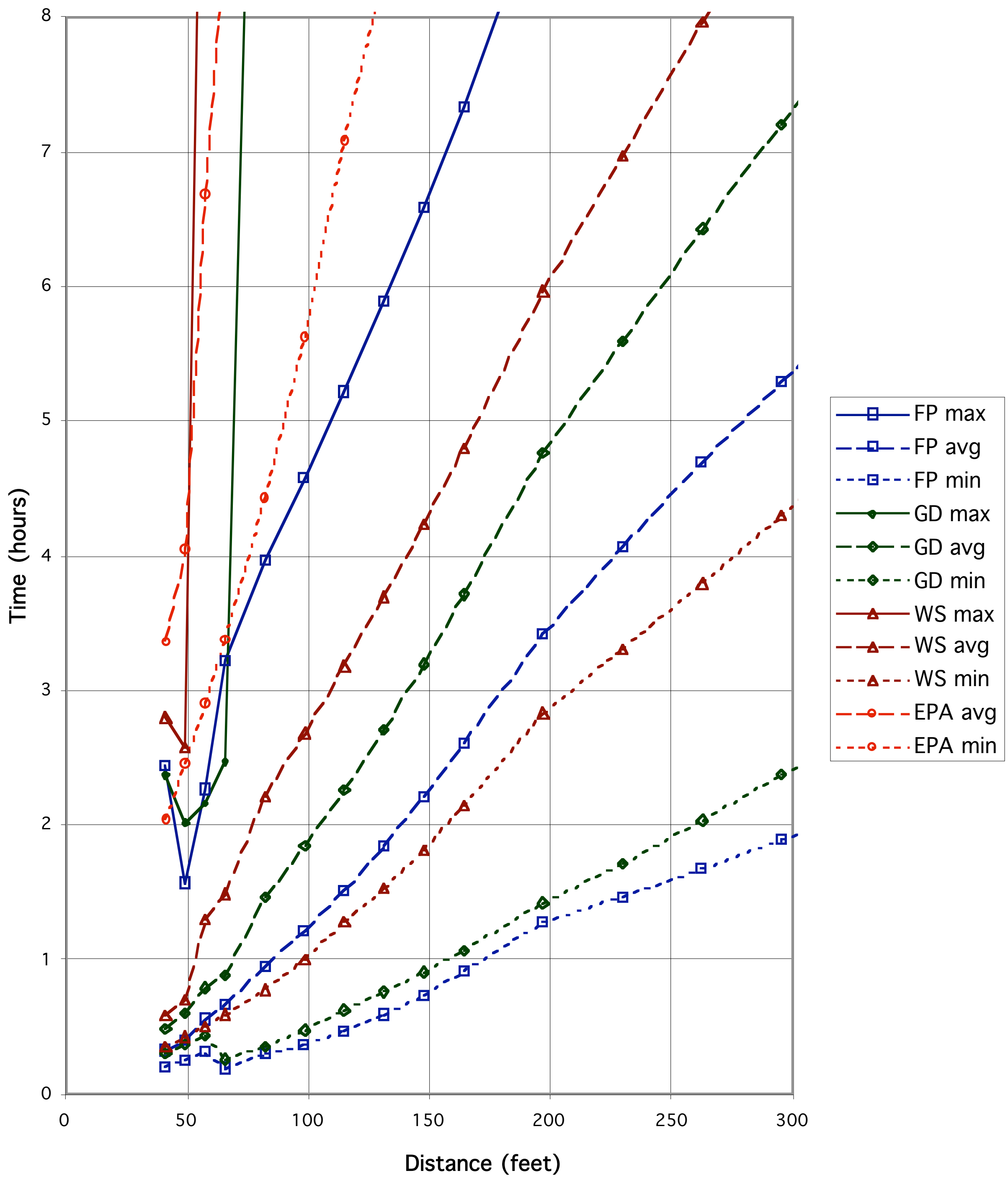
Wood burning efficiencies are from the BAAQMD wood burning handbook.[BA??] Efficiencies include the effect of heated room air being vented to the outside. The lower values are therefore primarily applicable to colder climates. Efficiencies used were 10% to 30% for a fireplace, 30% to 40% for a fireplace with glass doors, and 50% to 70% for a woodstoves or EPA inserts.

Screen3 results

The results were compiled over the range of input variables described above. The one run where the area variable was set to "urban" rather than "rural" is not included in these runs, because as mentioned earlier it was recommended that we use the "rural" value as being the appropriate value for Berkeley. The one "urban" run gave particulate concentrations that were on the order of 40% of those for the equivalent "rural" run, so the results reported here would need to be adjusted before they could be used in a more urban environment.

The length of time that a wood burning appliance might be used is not a fixed value, so the figures show the time that it takes to meet the air quality target level of 600 μg-hours/m^3. Figure 1 shows the burn times that correspond to the minimum, average, and maximum particulate concentrations for each of the four wood burning appliance types: standard fireplace, fireplace with glass doors to limit air flow, non-compliant wood stove, and EPA compliant wood stove or fireplace insert, as a function of the distance from the chimney. The maximum values for the EPA certified units are not shown as they all exceeded 8 hours. No times were shown for distances less than 40 feet. All the runs that are graphed used the standard downdraft option. Under this option a single value was reported for distances with in short distance of the building that were independent of terrain or receptor height. No values were available for a range of about 5 to 10 between the downdraft zone, and a minimum distance that depended upon the building height. Particulate concentrations in the downdraft zone were typically low, but has noted earlier this calculation is reported to be very conservative. The range of values shown arose from the variations in input values, such as building height, terrain elevation, the "receptor" elevation (this could be a person on the first or second floor of a nearby building), the size of the fire, and a host of lesser important variables. The curves for each wood burning appliance type summarize the results for from 20 to 200 separate calculations.

Figure 1: Duration of use after which operation of a wood burning appliance causes particulates to exceed air quality standards. Maximums for EPA certified units exceeded the scale on the graph and are not shown.



Of the variables that affect wood smoke emissions, some are fixed by the design of the fireplace or its location, while other depend upon its operation or other conditions. Some of the variables, such as the efficiency of the fireplace, and the ambient temperature, typically had less than a 2% effect on the calculated particulate concentrations and are not very important, but as can be seen from figure 1, this was not true for all of them.

Variables such as the size of the fire or the height of the receptor above the local terrain are not fixed for a given installation or its surroundings. Because these variables are not fixed, we have left them as sources of variability, and have not developed separate curves like those in figure 1 as a function of them, although they can make a significant difference to the particulate concentrations. For example, the particulate concentration is usually directly proportional to the size of the fire (wood burned per hour), however it also changes stack velocity and in one run had an effect that was almost four times what was expected. The receptor height variable accounts for whether a person is on the grounds of an adjoining property, or on a first or second floor. The effect of receptor height can be a factor of three, fifty to sixty feet from the chimney building, but diminishes to on the order of 10%, 300 feet from the building. The size and even the sign of the effect varies in a somewhat chaotic fashion in response to differences in chimney height and distance. Fire size and receptor height are the major residual sources of variability once site specific variables are accounted for.

Terrain elevation relative to the terrain, and building height are both fixed for a given installation and its surroundings, so an examination was made of particulate concentrations as a function of these variables. Separate plots were made for each that was significantly different from the remaining conditions. This evaluation was performed for each of the four wood burning appliance types. These plots are shown as figures 2 - 18. Each plot shows times corresponding to plus or minus one standard deviation in particulate concentration, as well as the minimum, average and maximum. The plus or minus one standard deviation curves typically enclose about 2/3 of the distribution of points.

Figure 2: Time to exceed air quality standard with a standard fireplace for a one story building surrounded by level terrain.

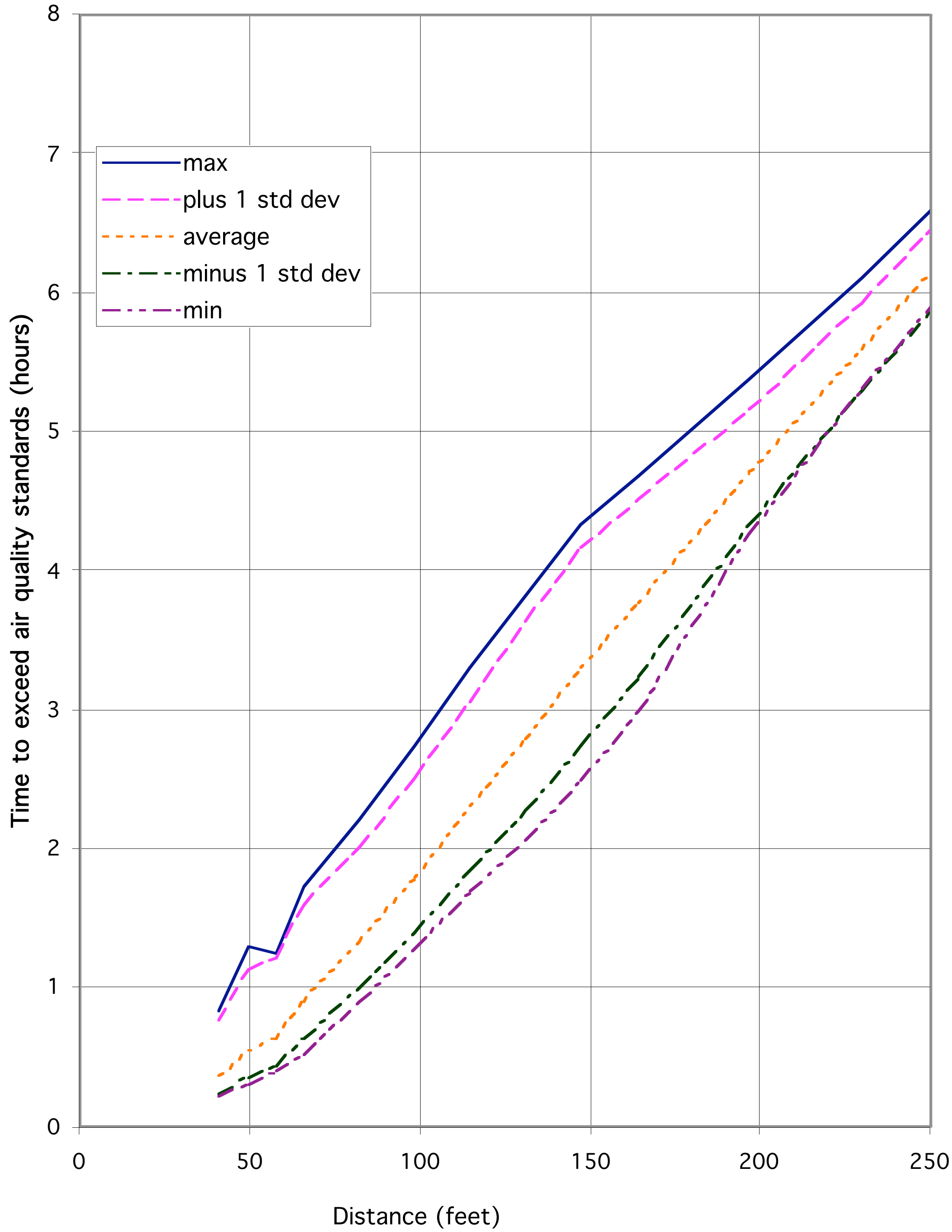


Figure 3: Time to exceed air quality standard for a standard fireplace a two or three story building surrounded by level terrain.

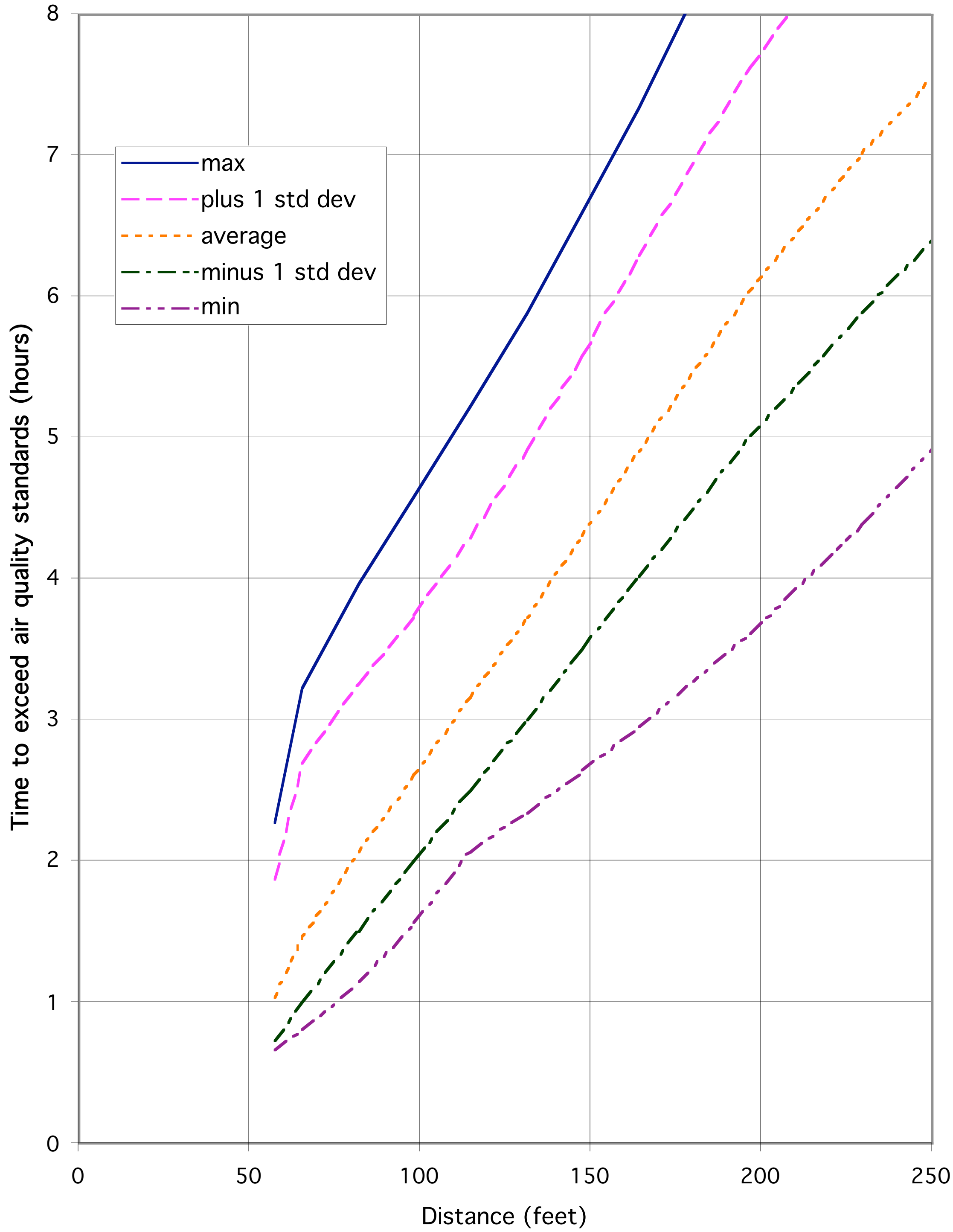


Figure 4: Time to exceed air quality standard upslope of a one story building with a standard fireplace.

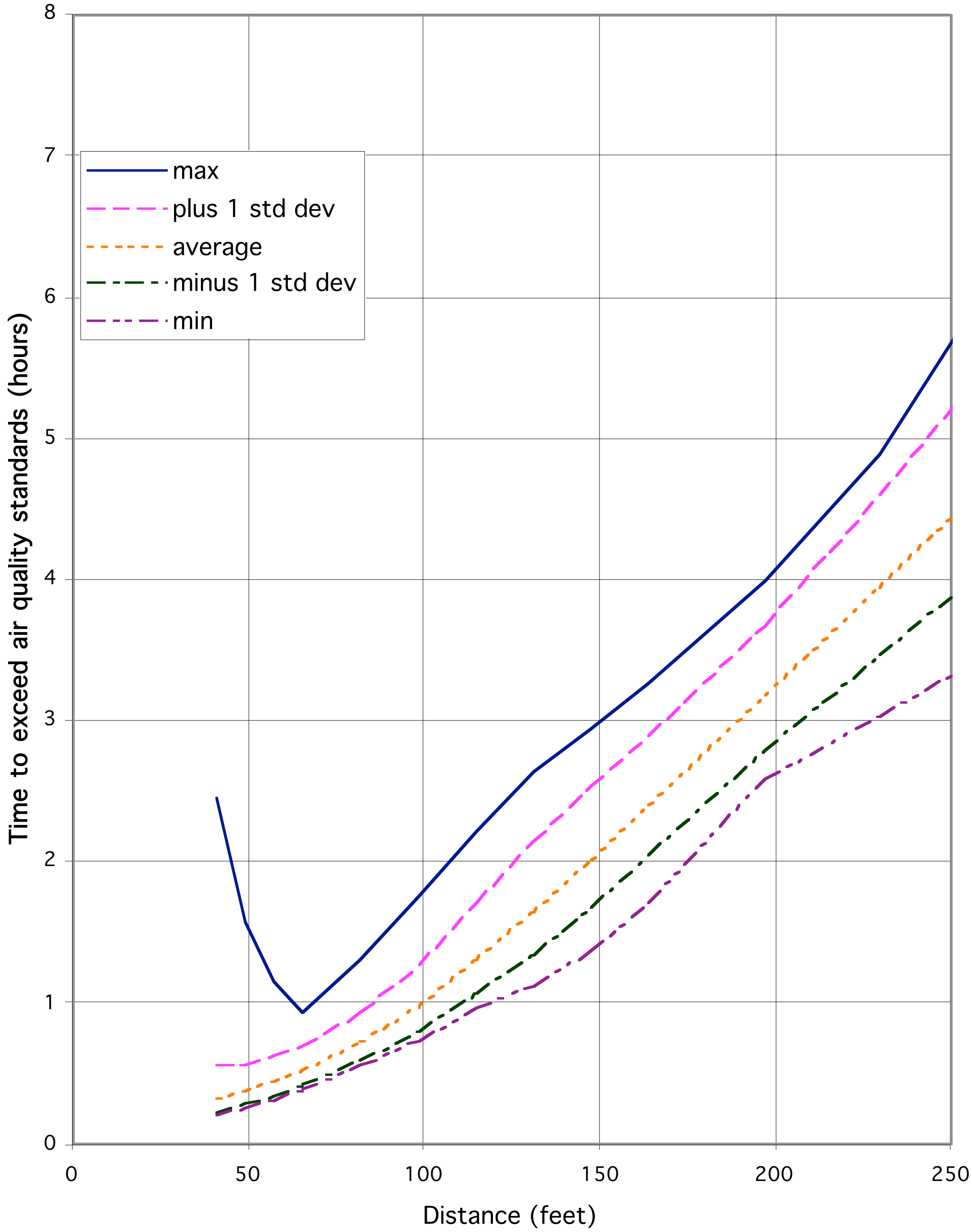


Figure 5: Time to exceed air quality standard upslope of a two or three story building with a standard fireplace.

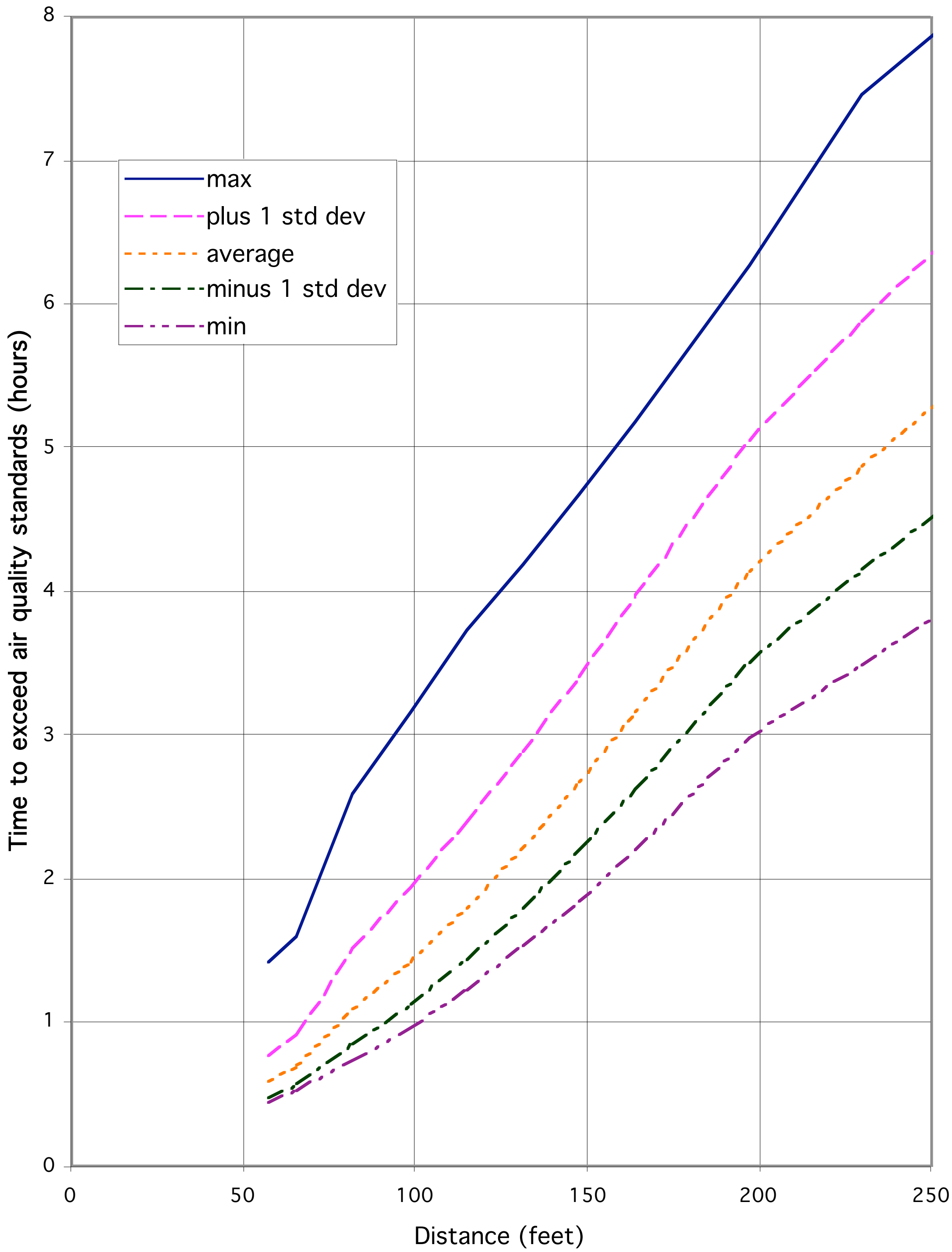


Figure 6: Time to exceed air quality standard with a fireplace with glass doors for a one story building surrounded by level terrain.

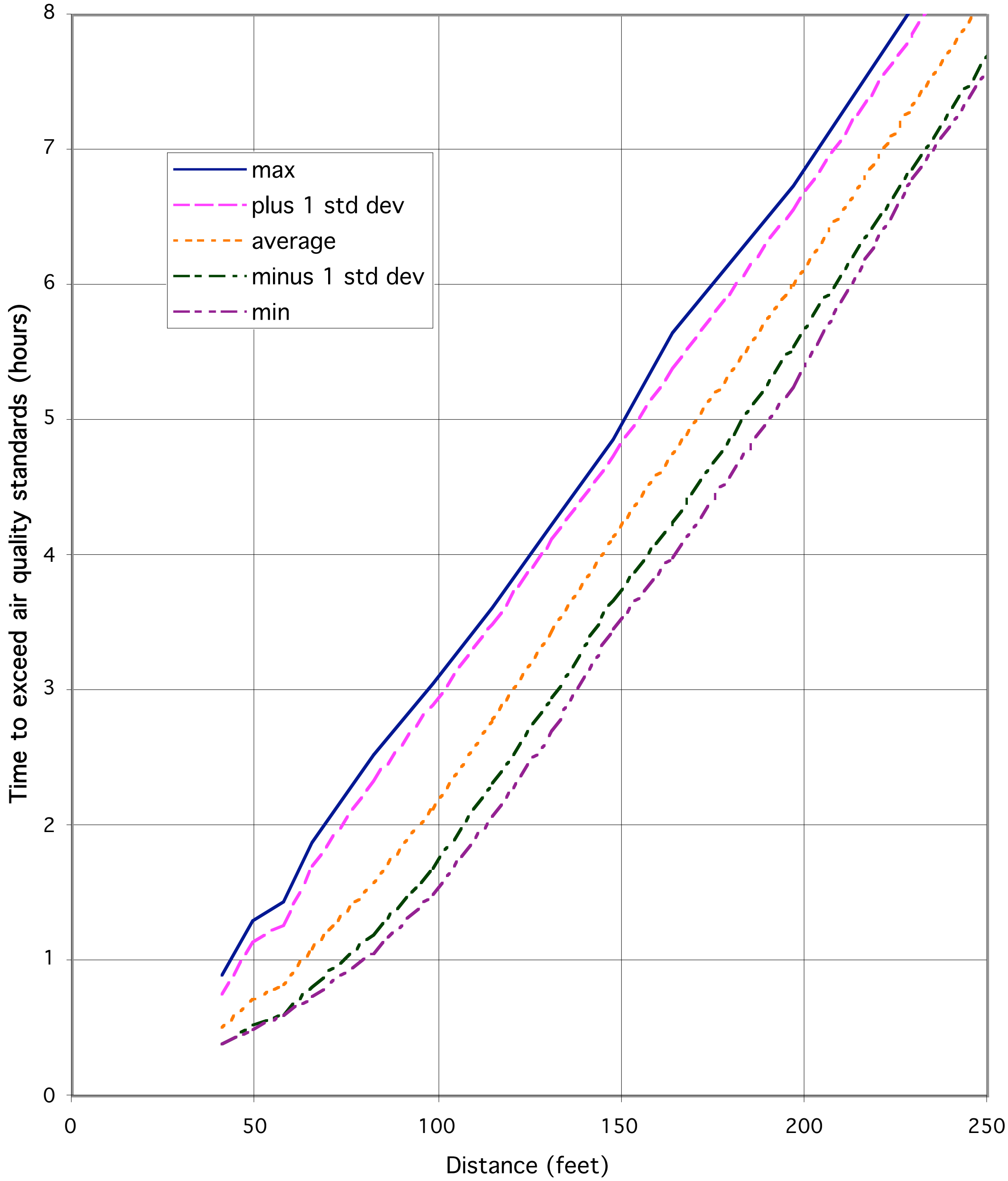


Figure 7: Time to exceed air quality standard with a fireplace with glass doors for a two story building surrounded by level terrain.

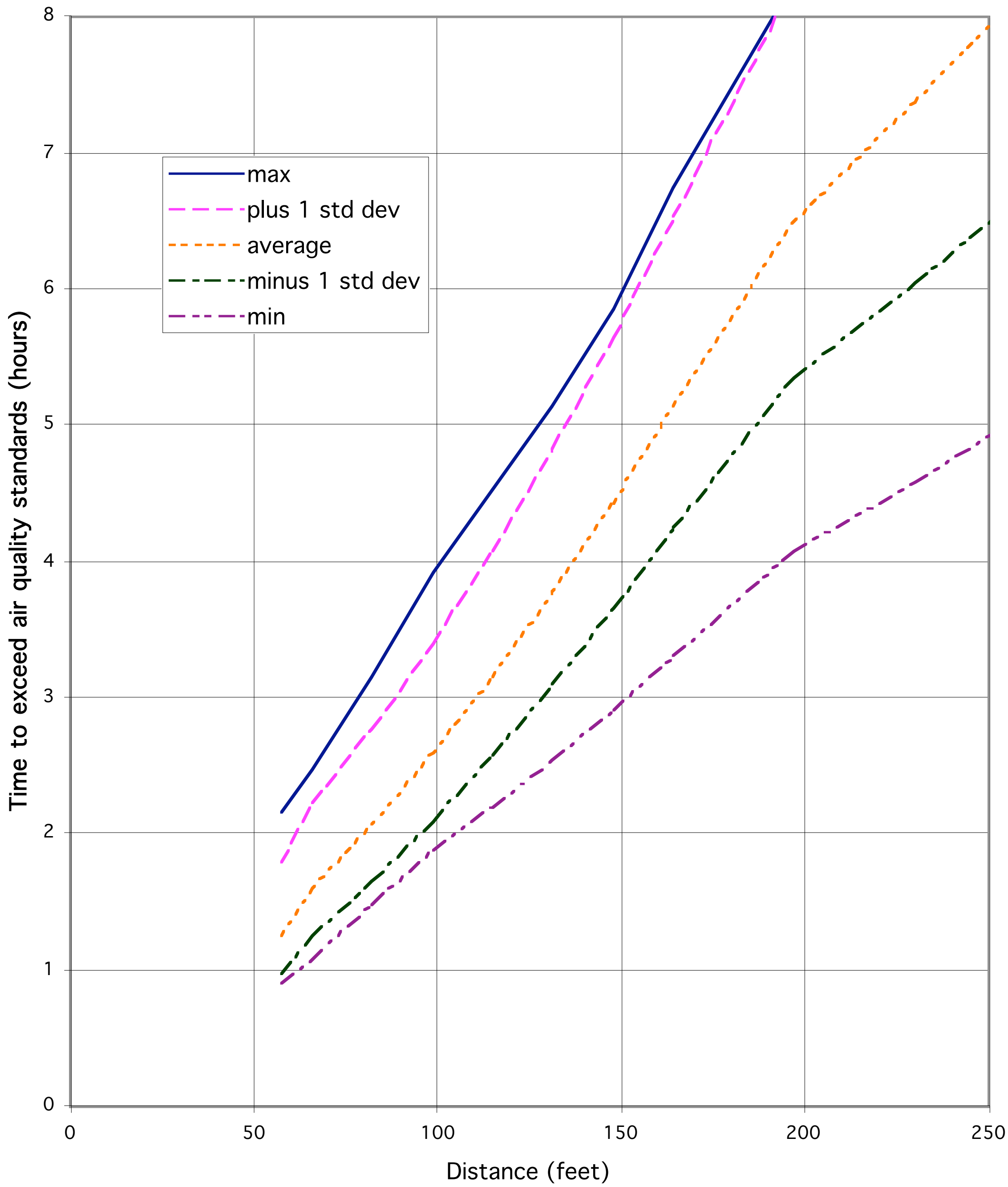


Figure 8: Time to exceed air quality standard with a fireplace with glass doors for a three story building surrounded by level terrain. The maximum and plus one standard deviation curves exceed the maximum value on the ordinate, and are not shown.

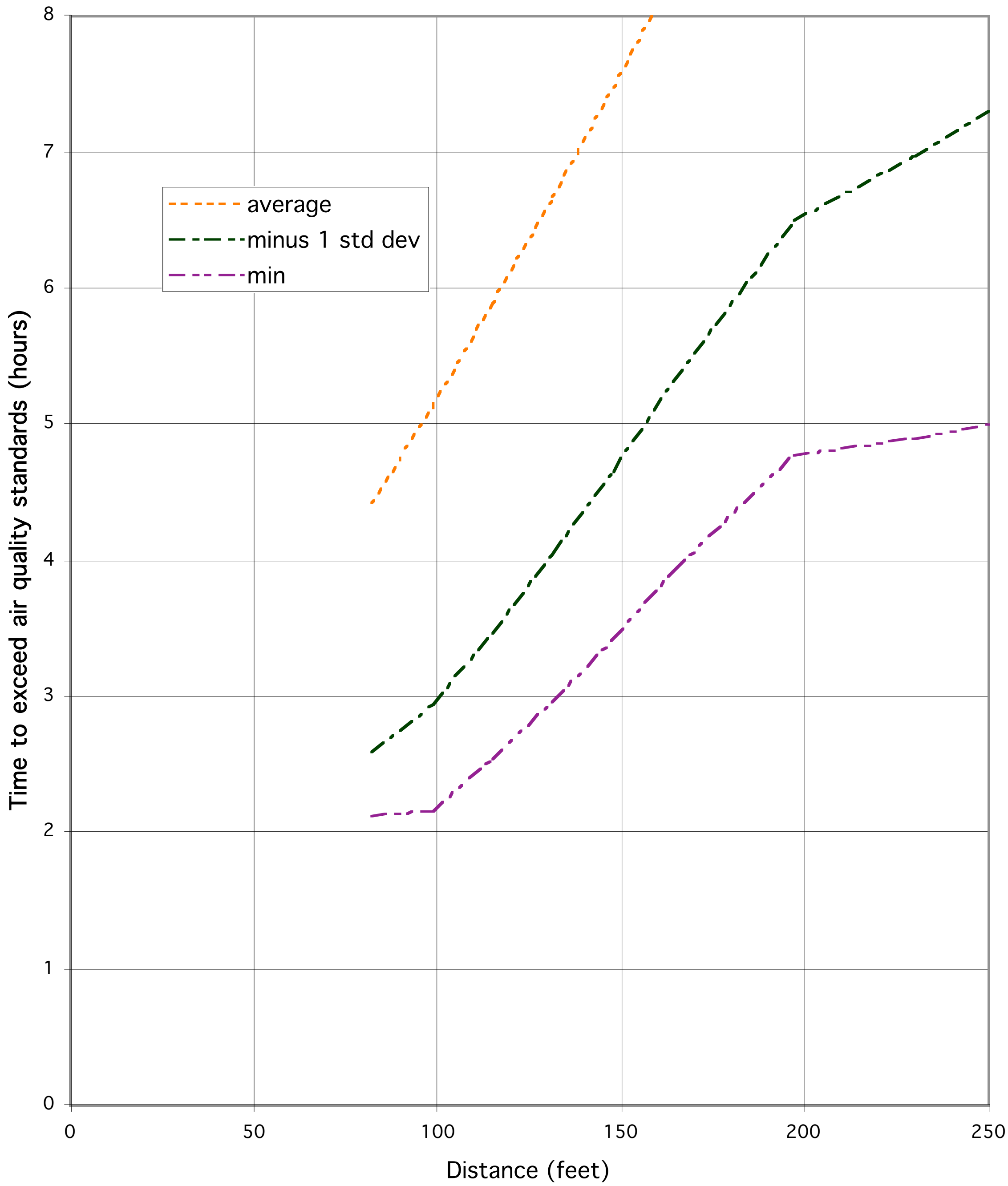


Figure 9: Time to exceed air quality standard upslope of a one story building with a standard fireplace with glass doors.

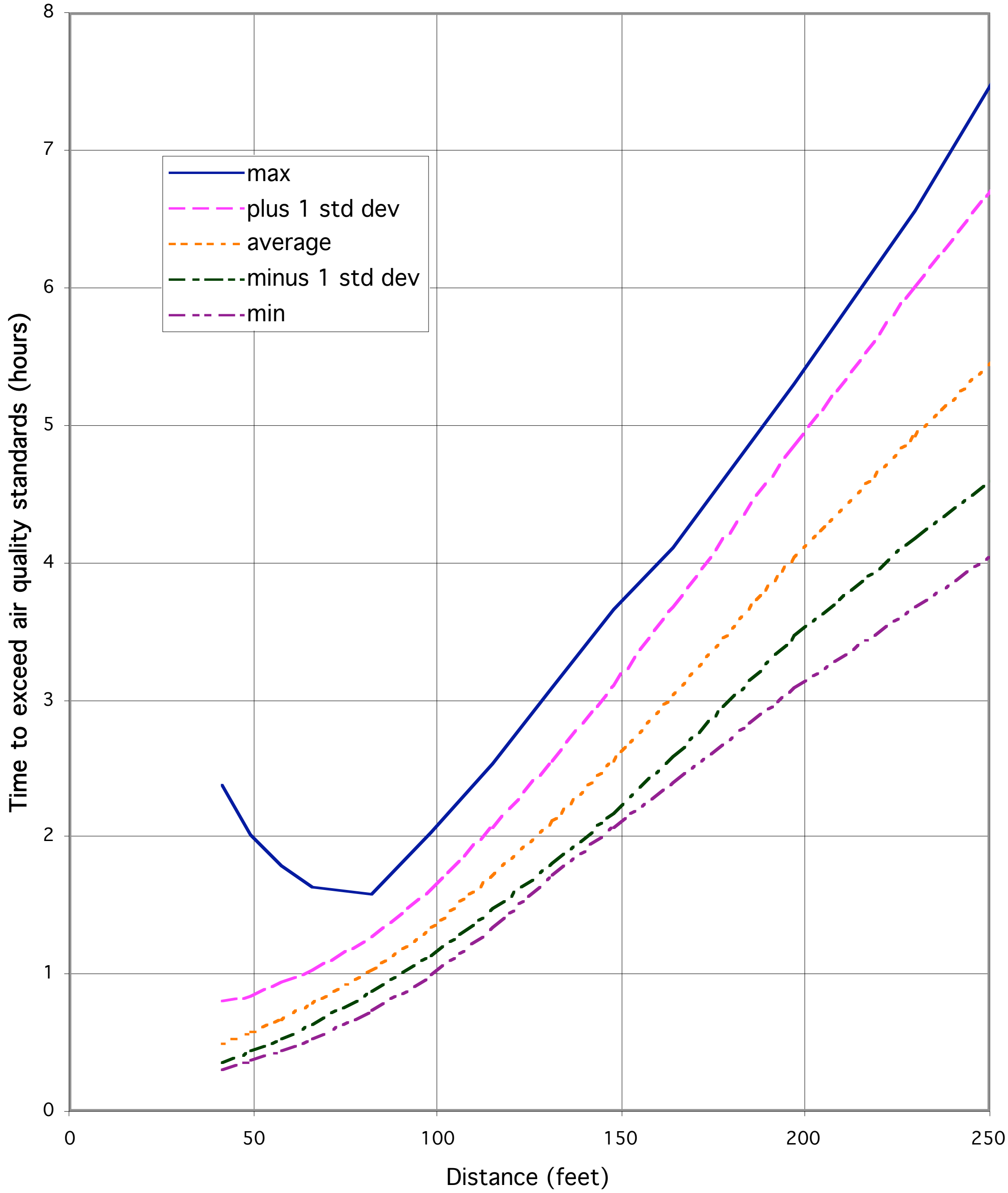


Figure 10: Time to exceed air quality standard upslope of a two story building with a standard fireplace with glass doors.

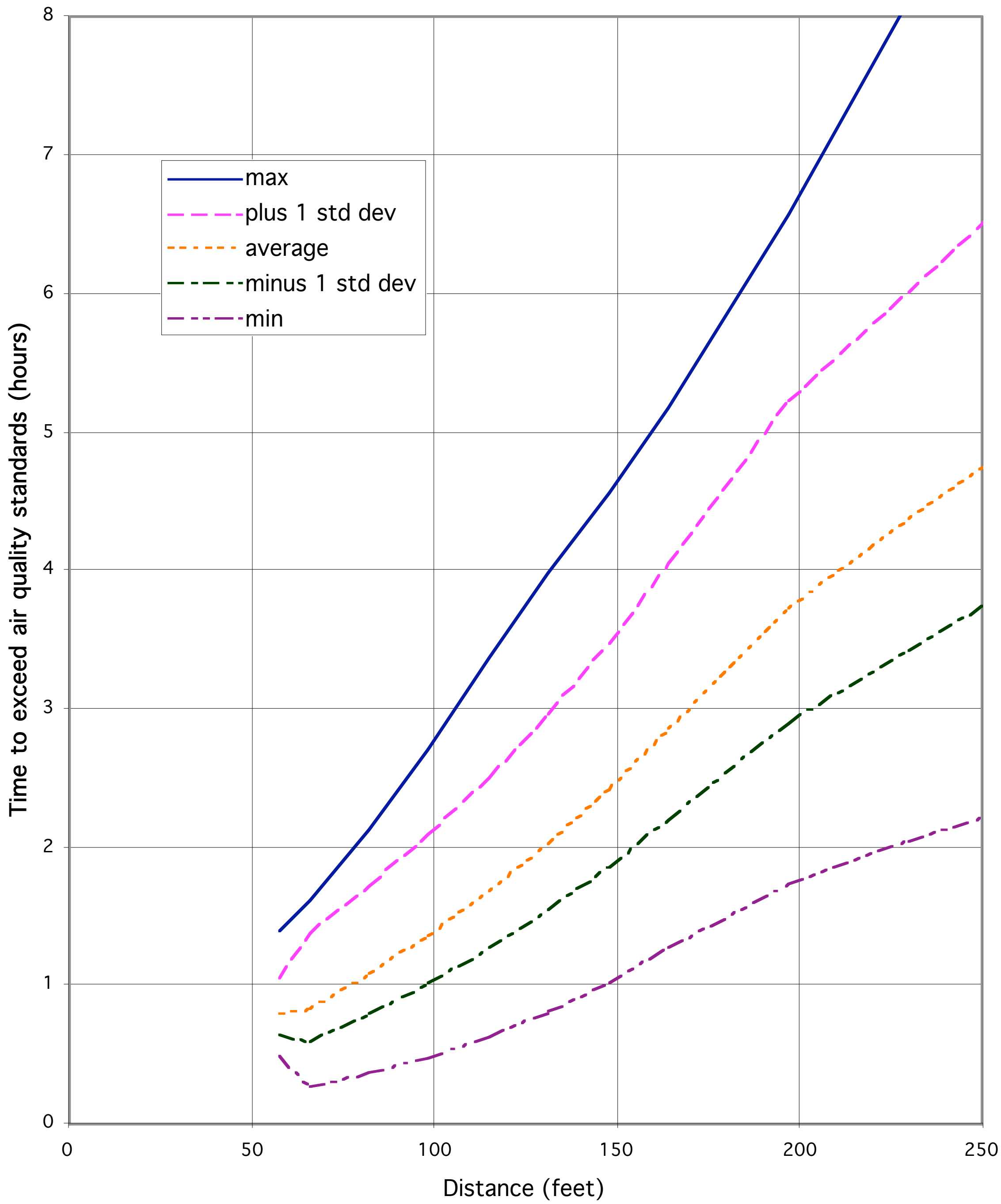


Figure 11: Time to exceed air quality standard upslope of a three story building with a standard fireplace with glass doors. The maximum and plus one standard deviation curves exceed the maximum value on the ordinate, and are not shown.

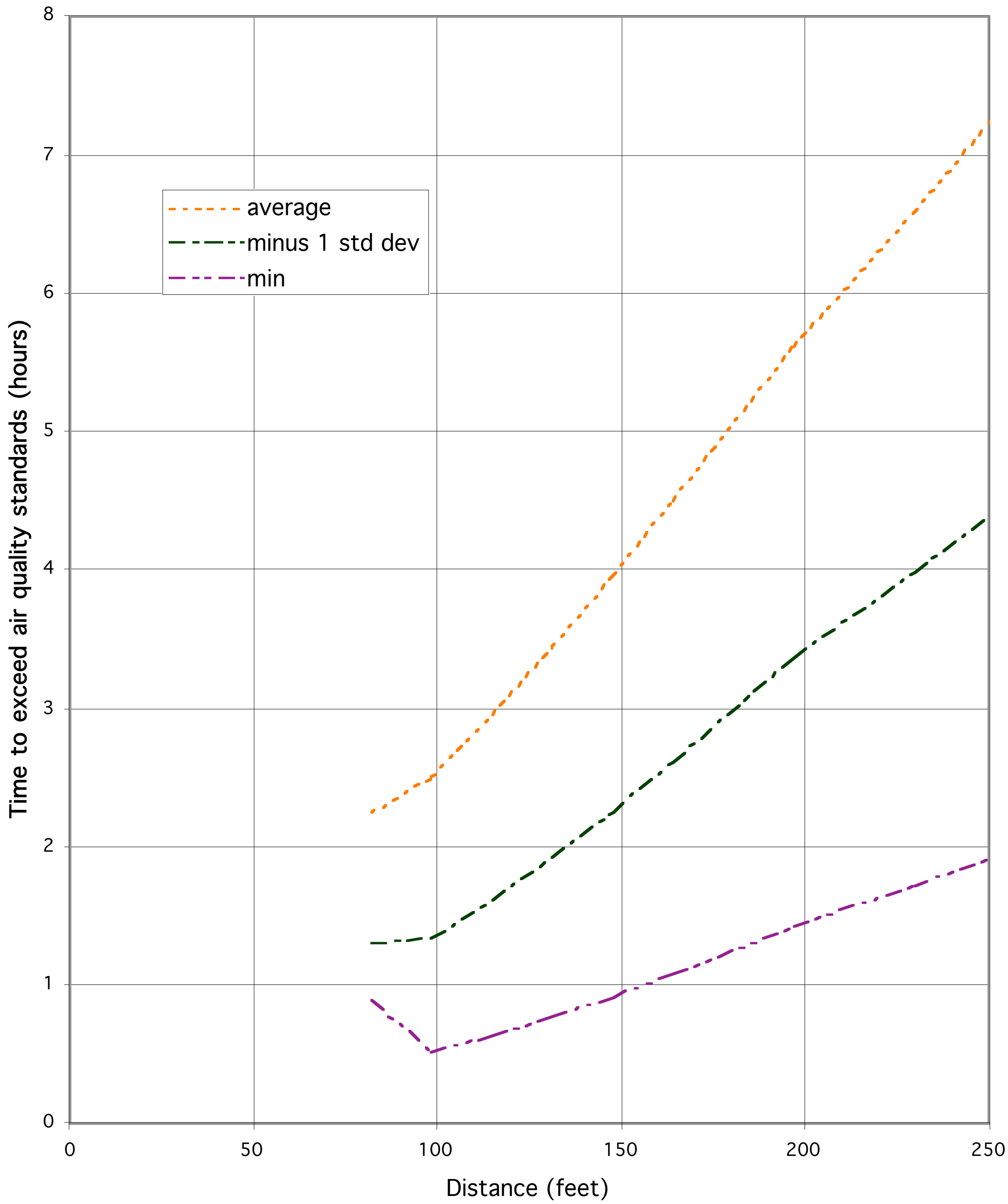


Figure 12: Time to exceed air quality standard with an uncertified wood stove for a one story building surrounded by level terrain.

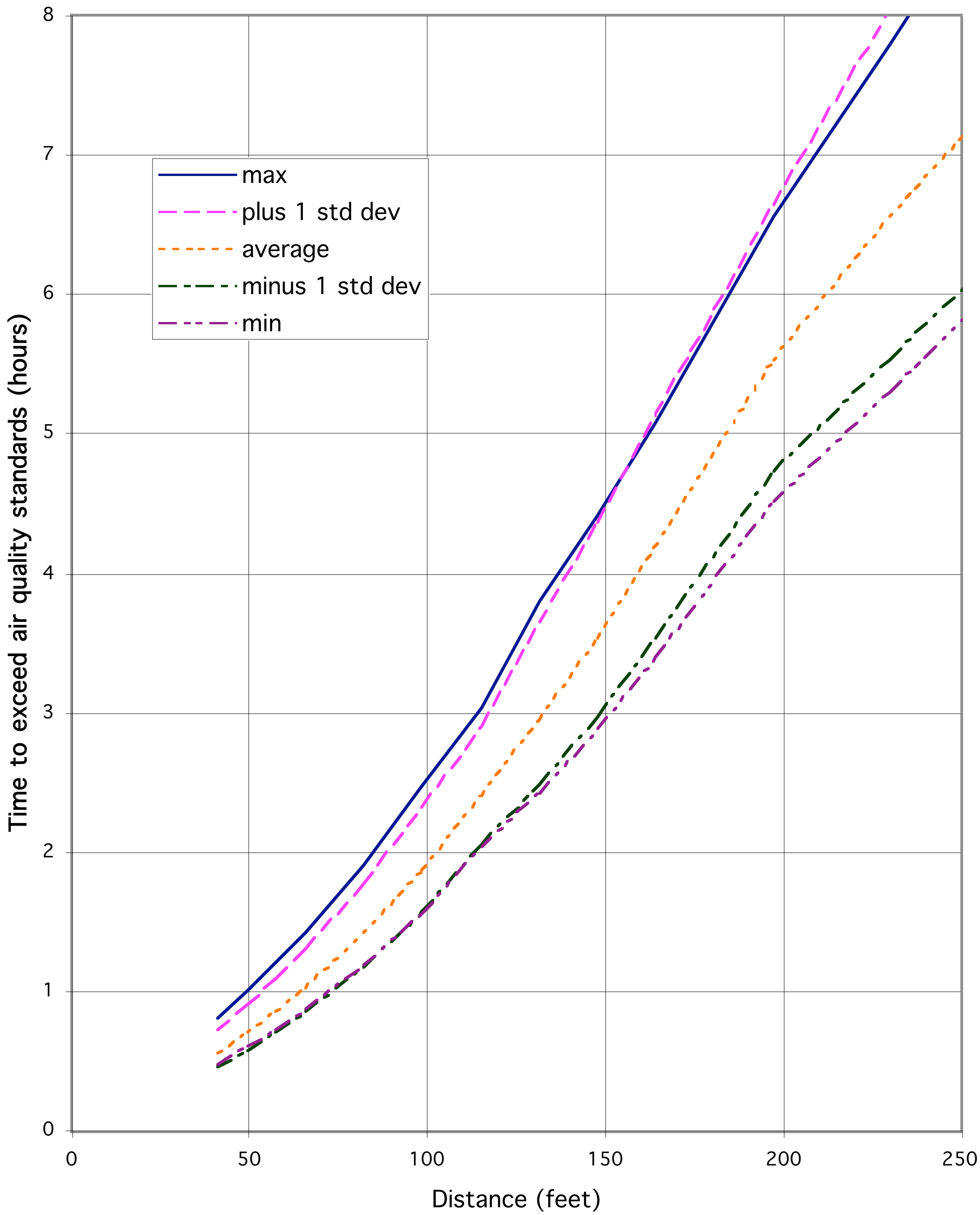


Figure 13: Time to exceed air quality standard with an uncertified wood stove for a two story building surrounded by level terrain. The maximum and plus one standard deviation curves exceed the maximum value on the ordinate, and are not shown.

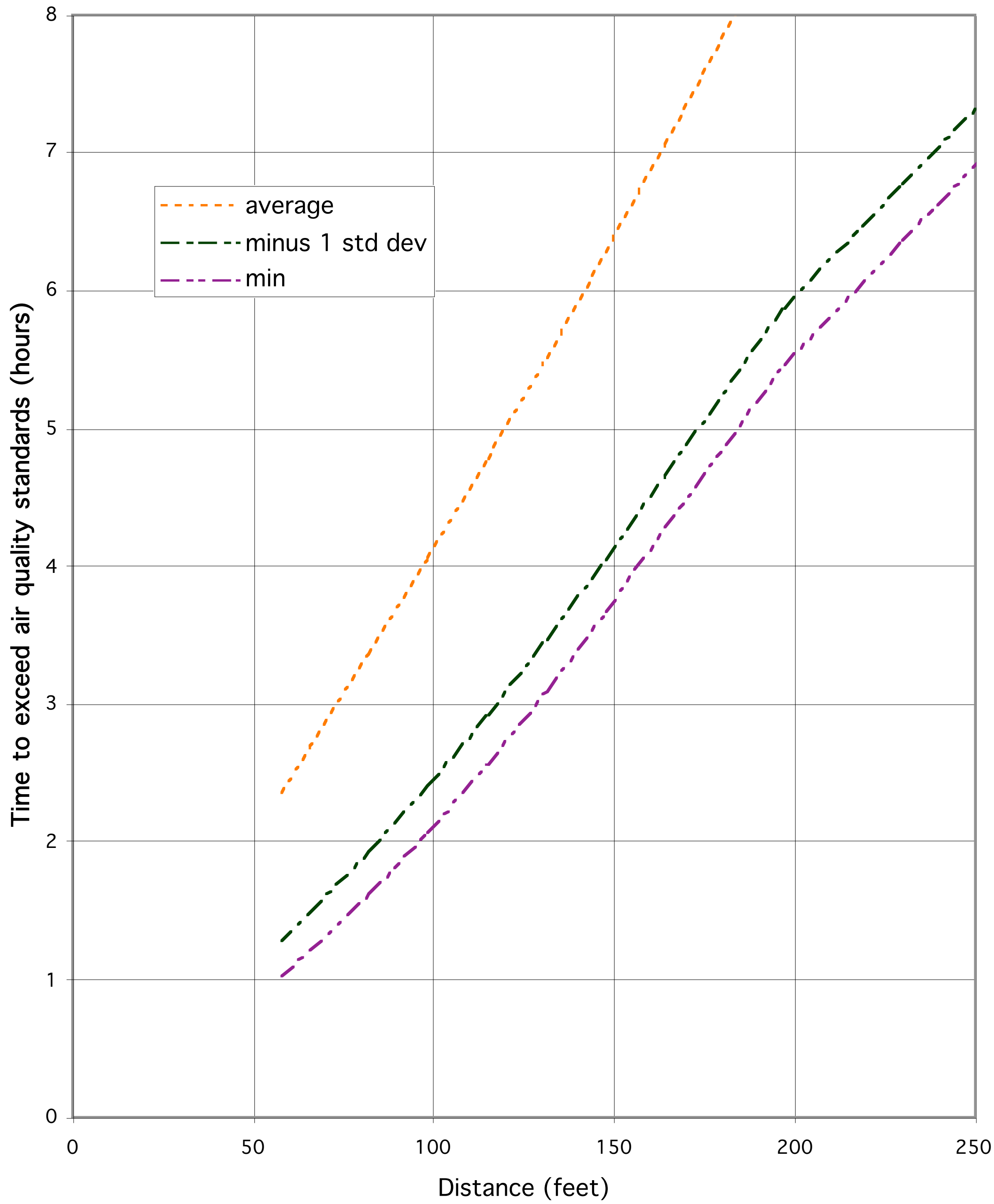


Figure 14: Time to exceed air quality standard with an uncertified wood stove for a three story building surrounded by level terrain. The maximum and plus one standard deviation curves exceed the maximum value on the ordinate, and are not shown.

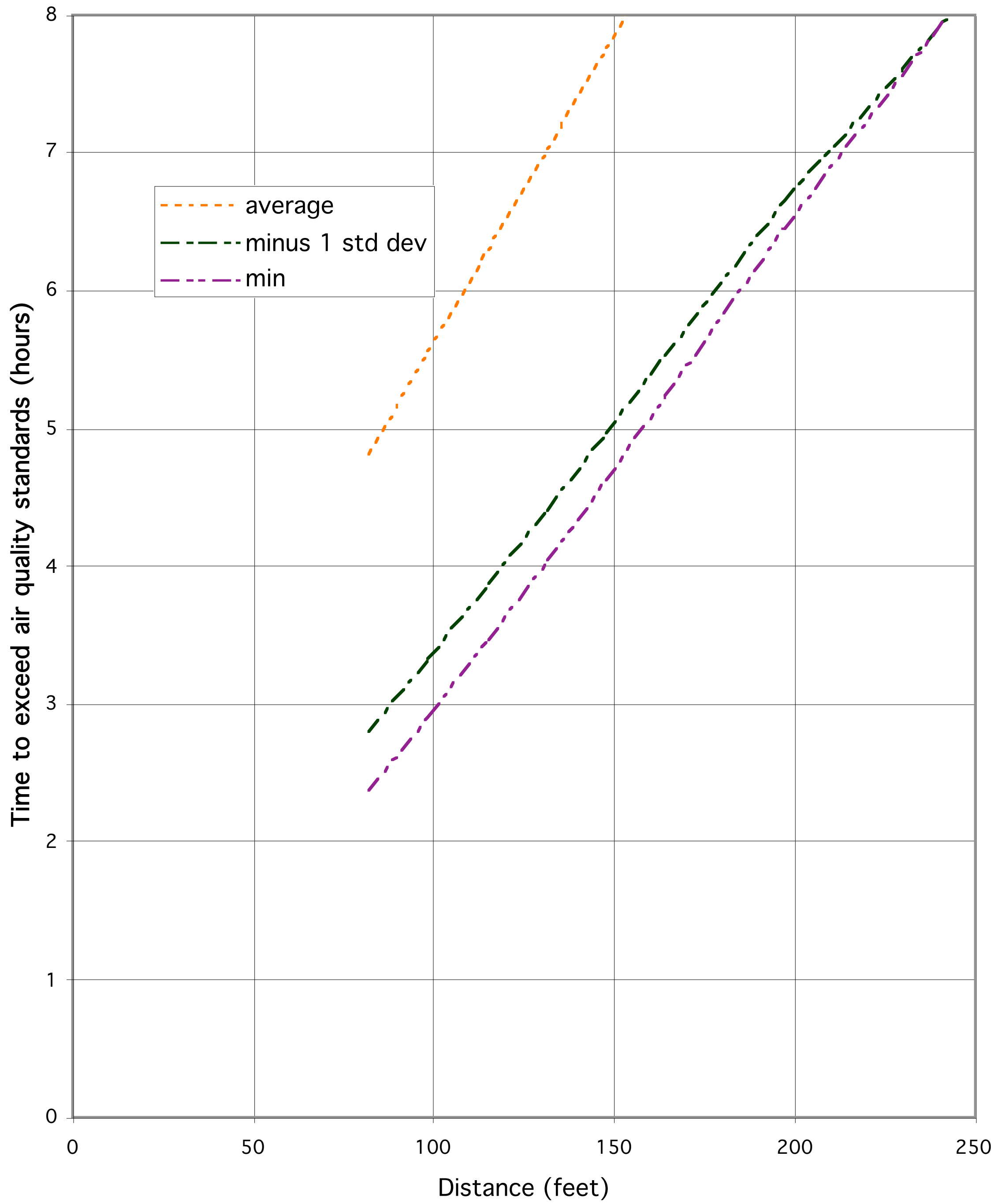


Figure 15: Time to exceed air quality standard upslope of a one story building with an uncertified wood stove.

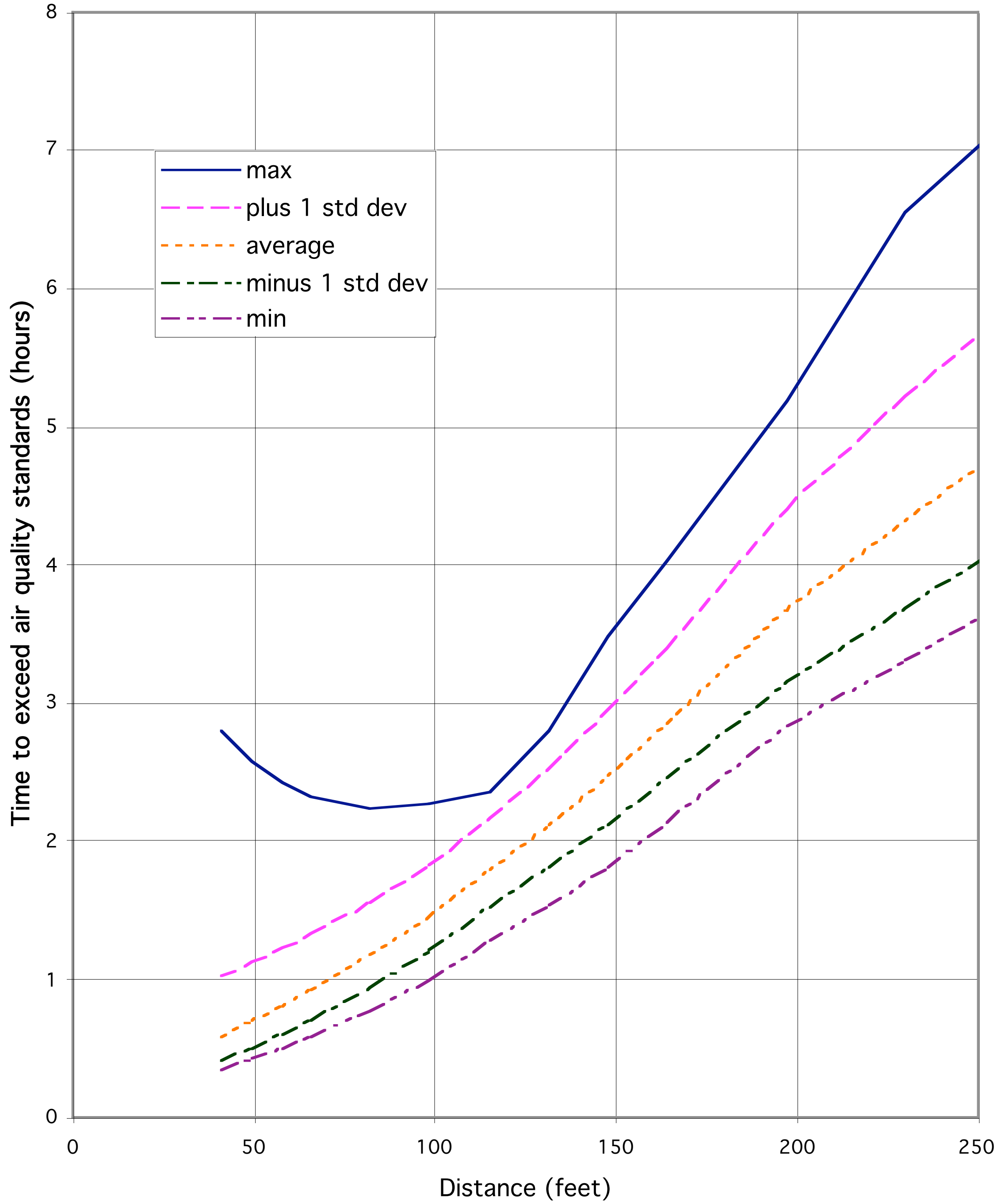


Figure 16: Time to exceed air quality standard upslope of a two story building with an uncertified wood stove. The maximum and plus one standard deviation curves exceed the maximum value on the ordinate, and are not shown.

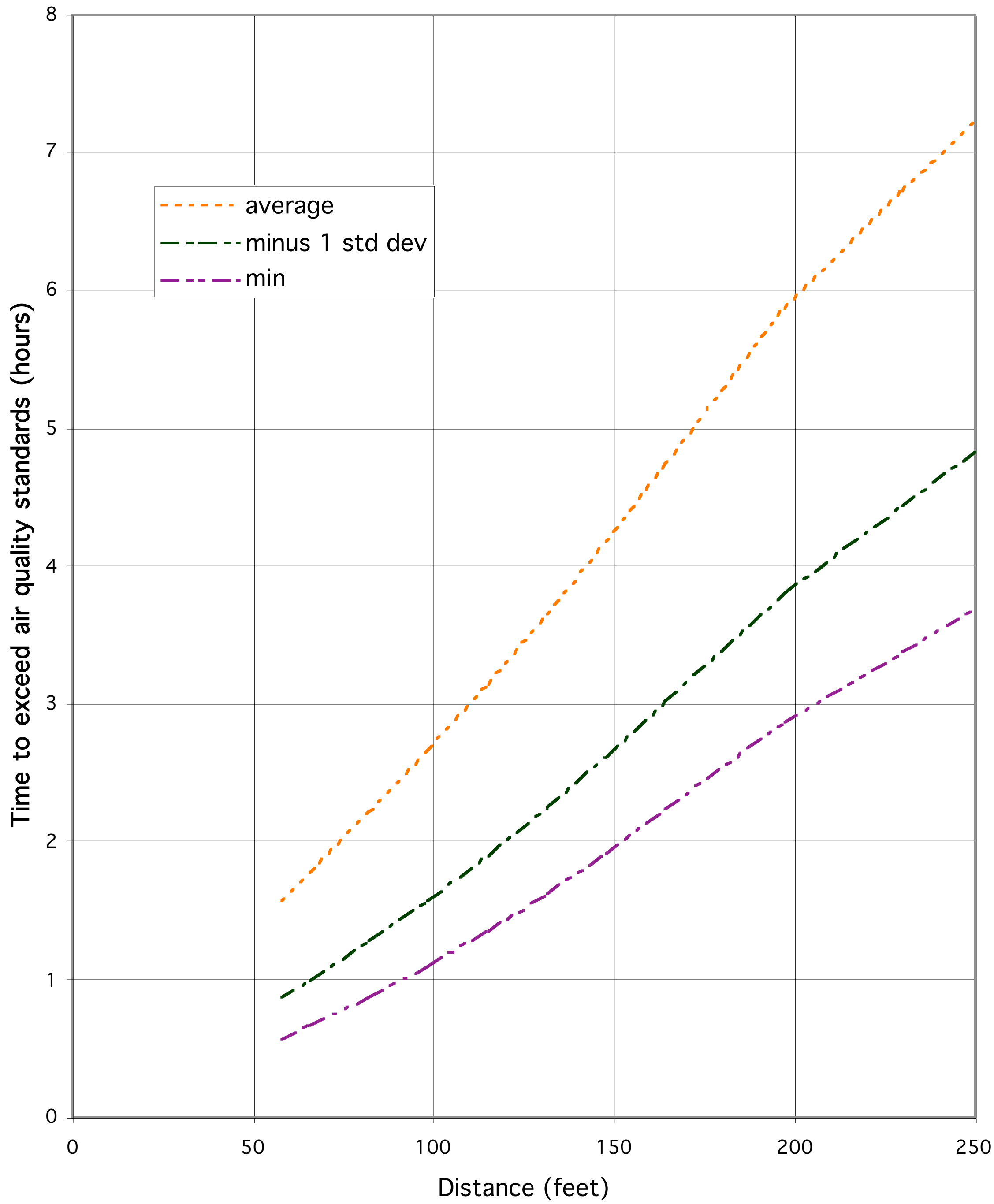


Figure 17: Time to exceed air quality standard upslope of a three story building with an uncertified wood stove. The maximum and plus one standard deviation curves exceed the maximum value on the ordinate, and are not shown.

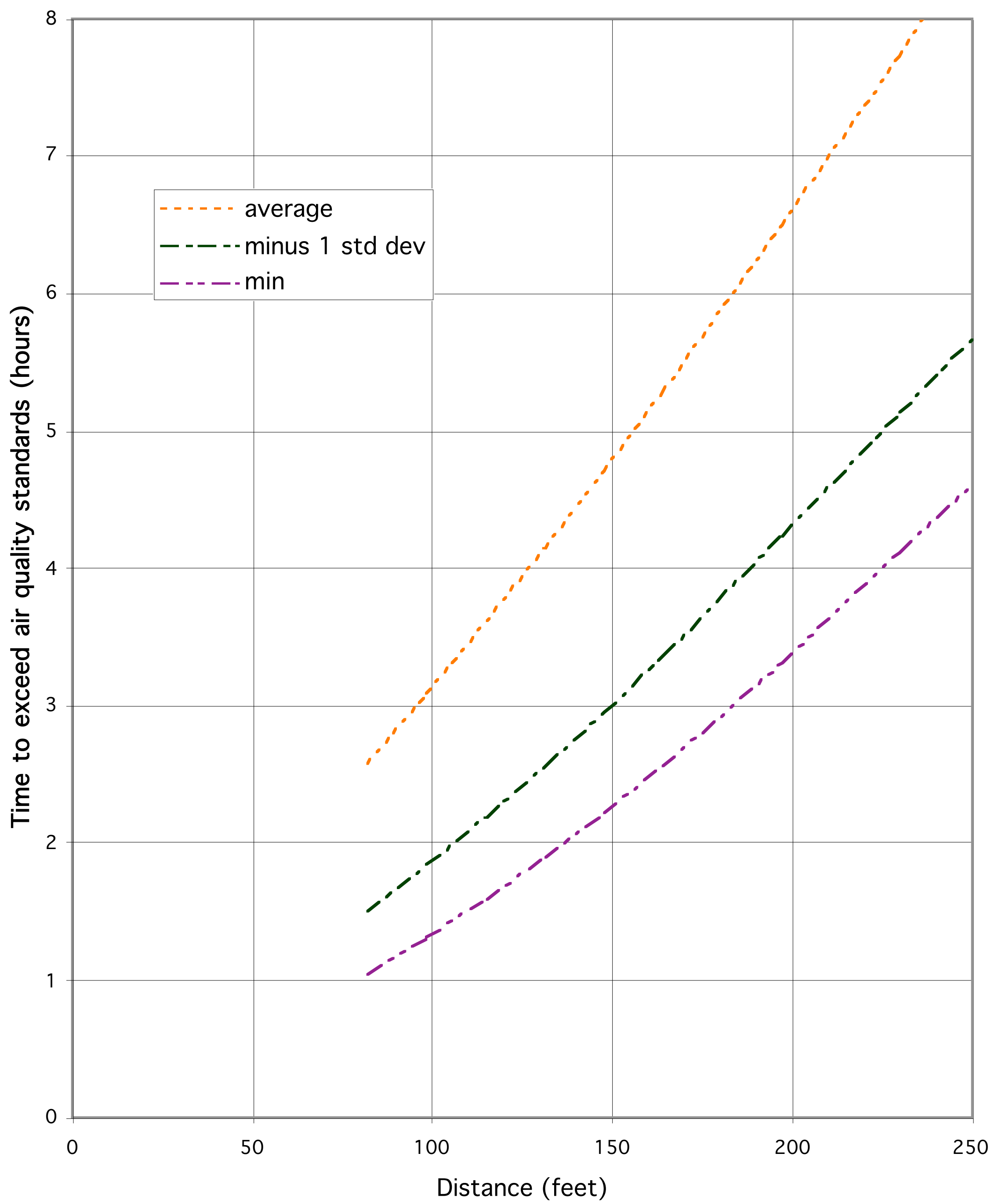
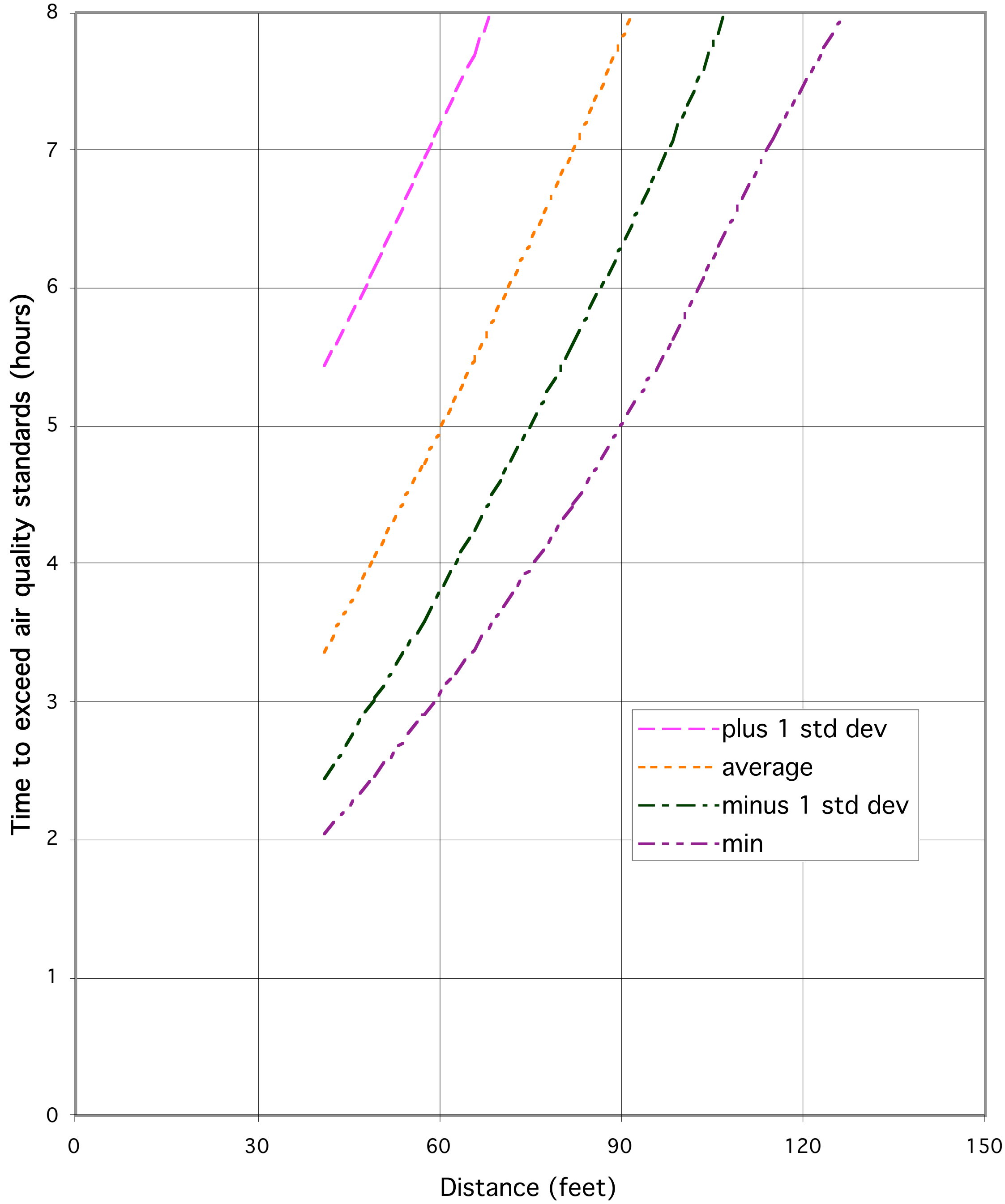


Figure 18: Time to exceed air quality standard for a one story building with an EPA certified wood stove or fireplace insert. The plus one standard deviation curve exceed the maximum value on the ordinate, and is not shown.

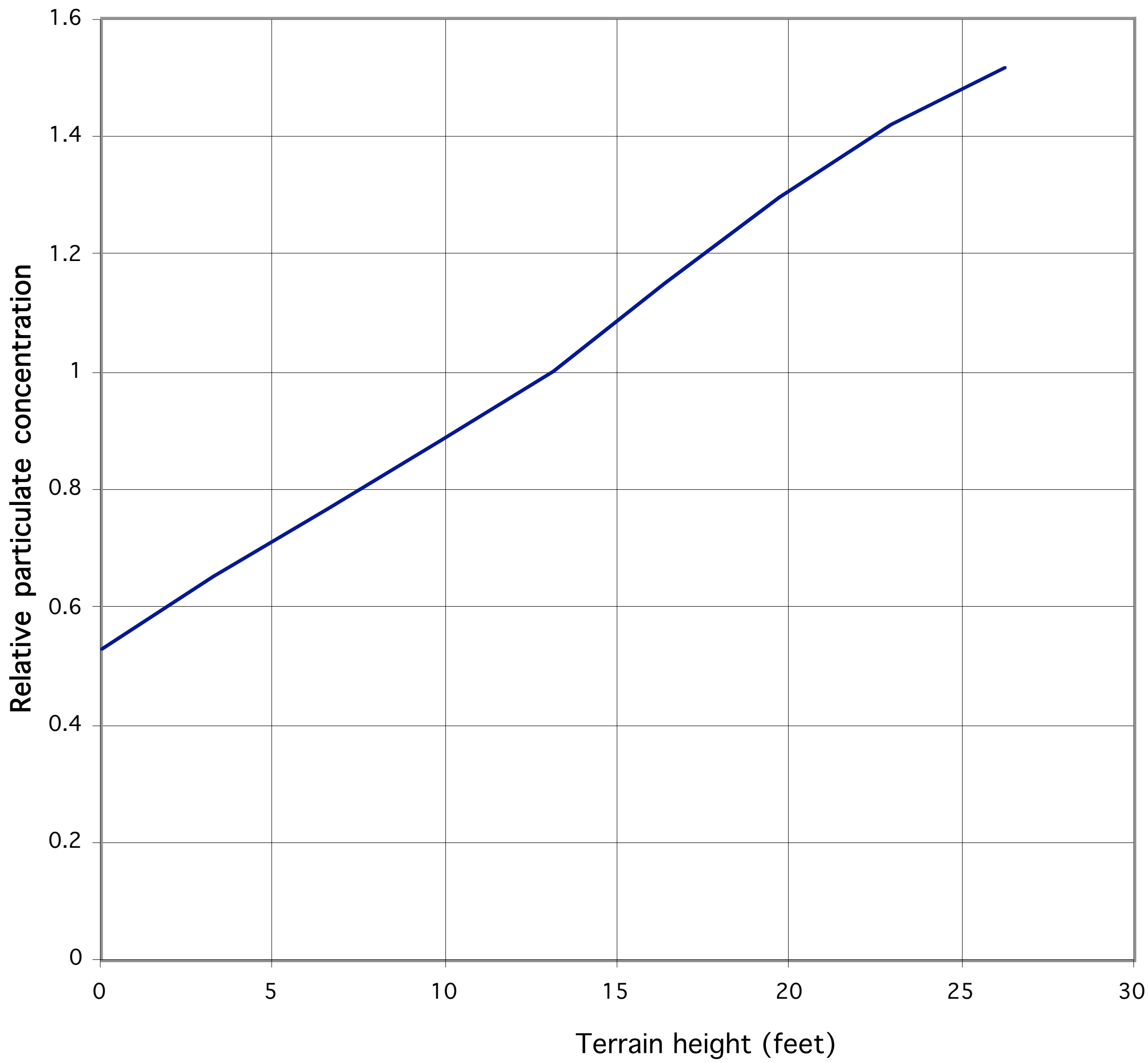


No curves are shown for EPA compliant stoves in two or three story residences, as the average time required to exceed the air quality standards is larger than 8 hours at all distances, and even the minimum time exceeds 3 hours.

The figures above do not cover the downdraft zone, and they do not cover downslope situations. The particulate concentrations in the downdraft region computed with the standard regulatory option for fireplaces averaged 150 μgrams/m^3. The concentrations are paradoxically about twice as large for two and three story buildings as they are for single story buildings. This would seem to suggest that wood smoke may be less of a problem for a really close neighbor, however when a subset of these calculations were rerun with the non-regulatory downwash option the concentrations in the downwash zone rose by nearly a factor of three. This is consistent with our correspondance with BAAQMD about the downdraft zone. The standard downdraft calculation is crude. The calculated values are independent of terrain height, distance and meteorological conditions, and are significantly lower than the values computed with the non-regulatory option. This suggests that the results in this region are not reliable.

The Screen3 program does not allow for calculations when the terrain slopes down from the chimney. The effect of terrain height depends strongly on the relative heights of the chimney and the receptor, and the distance from the chimney. For a single story building and distances within about 50 feet of the chimney the plume is compact, and the particulate concentrations are high at chimney height, and drop rapidly either above or below chimney height. Beyond 50 feet the plume broadens and lifts, with the result that even after including a range of receptor heights above the local terrain, there is still a general trend towards lower particulate concentrations for lower terrain heights. As distances continue to increase the effect of terrain height becomes increasingly smaller, but it is still significant at 330 feet, which was the largest distance calculated in this study. At the distances of interest, terrain height effects were generally comparable to other sources of variation, and therefore for simplicity, the summary figures were plotted versus only two categories of terrain height, level and upslope. However, differences in terrain height become increasingly important as terrain height becomes smaller. Figure 19 shows the trend of particulate concentrations averaged over distances for 40 to 330 feet for fireplaces as a function of terrain height:

Figure 19: Relative particulate concentration versus terrain height (distances 40 to 330 feet)



The trend is approximately linear with terrain height, with an extrapolated zero at about negative 15 feet. It is clear that extrapolation will overestimate the effect of terrain for major downslopes, as particulate concentrations can not go negative. Figure 19 suggests that the for down slopes of 5% (5 feet in 100 feet) particulate concentrations will be about 20% lower than for level terrain. Extrapolation beyond this slope is unlikely to be valid.

As we noted earlier, the efficiency of the wood burning appliance in providing heat has little effect on particulate concentrations nearby. We examined efficiencies varying from a low of 10% for fireplaces to a high of 70% for an EPA certified unit, and found variations of 1.5% or less in the concentrations. However, if the wood burning appliance is being used for heating, the efficiency will make a difference in the size of the fire, or the amount of time that it is used.

Meteorlogical conditions can have a very significant impact on the computed particulate concentrations. The Screen3 program normally picks the meteorlogical condition which leads to the highest particulate concentrations. Changes in the size of the fire, with its associated changes in exhaust flow rate and speed, and exhaust temperature, can lead to changes in the meteorolgical conditions which give the highest particulate concentrations. Thus, while we normally found that particulate concentrations were approximately proportional to the size of the fire, in one case a change in meteorolgical conditions resulted in an almost four times larger change than expected.

Voluntary restrictions on wood burning on still air days, which is the meteorlogical condition mostly likely to cause problems, have been in effect for some time, and the BAAQMD is currently considering making these restrictions mandatory. To determine whether this restriction would eliminate the local air quality problem shown in our results above, I ran a set of runs with a standard fireplace in a single story house over a range of wind speeds, stability conditions and terrain elevations, and a fixed receptor height of 2 meters (6.5 feet).

The stability conditons range from very unstable (A) to stable (F).[WI07] Stability is determined by windspeed and the radiative conditions. Table 6 from Wikipedia shows the conditions that define the stabilty classes.

Table 6: Meteorological conditions that define the stability classes

Windspeed	Daytime solar radiation			Nighttime cloud cover	
miles/hour	Strong	Moderate	Weak	>50%	<50%
<5	A	A-B	B	E	F
5-7	A-B	B	C	E	F
7-11	B	B-C	C	D	E

11-13	C	C-D	D	D	D
>13	C	D	D	D	D

Screen3 permits runs with stability classes C and D and windspeeds less 5 miles per hour, and this presumably applies to the transition period between night and day. Screen3 does not permit runs with stability classes A and F with windspeeds above 7 miles per hour, or classes B and E with windspeeds above 11 miles per hour.

The basic effect of the meteorological conditions is shown in table 7. The data for table presents the distance at which the particulate concentrations exceed the air quality standards in three hours for a one story house.

Table 7: The distance at which the particulate air quality standard is exceeded in three hours. There were five terrain elevations for each meteorological condition in the table. The distances shown are the averages (in feet) over the 5 terrain elevations calculated for each meteorological condition. The averages only include those conditions where the air quality standard was exceeded. The numbers in parentheses are the number of cases (out of 5 possible) that are included in the average. Conditions which are not legitimate combinations of windspeed and stability are note as not applicable (NA).

	Windspeed (miles per hour)		
Stability	2.2	5.6	11.2
A	63(3)	(0)	NA
B	80(4)	44(3)	(0)
C	128(4)	64(4)	(0)
D	168(5)	85(5)	52(3)
E	90(5)	105(5)	64(4)
F	103(5)	150(5)	NA

No entries are shown for windspeeds of 22 miles per hour, as the minimum time at the minimum distance of 40 feet was 4.5 hours. Table 7 shows that a wood burning appliance is unlikely to cause a local air quality problem when average windspeeds are moderate to high (10 miles per hour or greater). At windspeeds on the order of 6 miles per hour, woodsmoke can be a problem at night or dawn or dusk (neutral to stable atmospheres). At low windspeeds woodsmoke is likely to be a problem except under conditions of strong solar insolation (very unstable atmosphere).

Discussion

The first and most important point to make based on the runs shown here is that they confirm our original concern that woodsmoke from a chimney is capable of producing a local problem while background levels remain below the level of regulatory concern. The rapid decline of concentration with distance demonstrates that treating wood smoke as a purely regional problem can lead to significant underestimation of its health effects, with a fraction of the population that is adjacent to a wood burning appliance being exposed to particulate levels that can be far in excess of regulatory limits.

A second important point is that it does not appear that making "spare the air nights" mandatory will prevent local problems. Woodsmoke can be a problem even under unstable atmospheric conditions if windspeeds are low, and can still be a problem under neutral conditions at moderate windspeeds. Bans on woodburning due to meteorological conditions would have to be extended to even fairly moderate conditions to prevent air quality problems. In fact, even this would not be sufficient. The figures show that under some conditions air quality standards can be violated in as little as fifteen minutes. This means that air quality district has to be able to predict the meteorological conditions in advance to prevent air quality problems. Furthermore the Bay Area is known for its microclimates: "... If you don't like the weather, walk a few miles.", so a ban on wood burning based on regional conditions may not be sufficient for numerous small areas within the region.[NH04]

The calculations here do not cover situations where there intervening buildings between a receptor and the chimney, and they do not cover valleys. Woodsmoke concentrations are likely to be less if you are downslope from a chimney, but the calculations do not appear to be appropriate for a capping inversion over a basin.

Figures 2 through 18 showed the time required to exceed the air quality standards as a function of distance for the different wood burning appliances, building heights and slopes. A wood fire in a fireplace or stove will generally last several hours. Table 8, below, summarizes the data in the figures by listing distances for which the air quality standard is exceeded in three hours. The table lists lists the average and the plus or minus one standard deviation points. The minimum and maximum points are much more prone to sampling error than these distribution measures, and are not shown in the table.

Table 8: Distance to exceed the air quality standard in three hours. The distribution is over receptor heights, variations in terrain (for the upslope condition), plus variations in temperatures, burn rates, and efficiencies.

Appliance	terrain	# stories	-1 σ	average	+1 σ
Fireplace	level	1	110	140	160
Fireplace	level	2+	70	110	130
Fireplace	upslope	1	170	190	210
Fireplace	upslope	2+	130	160	180
Glass doors	level	1	100	120	130
Glass doors	level	2	90	110	130
Glass doors	level	3	None	None	100
Glass doors	upslope	1	140	160	180
Glass doors	upslope	2	130	170	200
Glass doors	upslope	3	None	120	180
Unc. Wood stove	level	1	120	130	150
Unc. Wood stove	level	2	None	70	120
Unc. Wood stove	level	3	None	None	90
Unc. Wood stove	upslope	1	150	170	190
Unc. Wood stove	upslope	2	None	110	160
Unc. Wood stove	upslope	3	None	100	150
EPA certified	all	1	None	None	50
EPA certified	all	2+	None	None	None

Table 8 shows that EPA stoves are almost never likely to cause an exceedance of the air quality standards. Open air fireplaces will cause exceedances under some meteorological conditions, while the other two classes of wood burning appliances will cause exceedances under some, but not all combinations of building height and slope.

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