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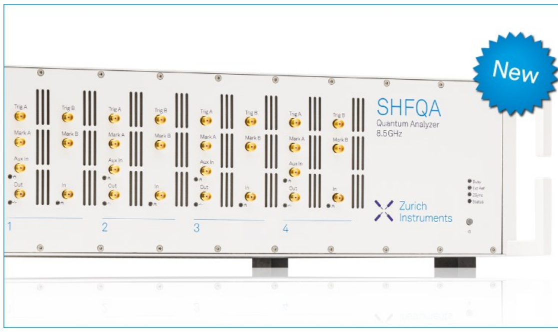

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Investigating Environmental Impacts of Particle Emissions from a High-Temperature Falling Particle Receiver

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Abstract. Particle emissions from a high-temperature falling particle receiver with an open aperture were modeled using computational and analytical methods and compared to U.S. particle-emissions standards to assess potential pollution and health hazards. The modeling was performed subsequent to previous on-sun testing and air sampling that did not collect significant particle concentrations at discrete locations near the tower, but the impacts of wind on collection efficiency, especial for small particles less than 10 microns, were uncertain. The emissions of both large (~350 microns) and small (<10 microns) particles were modeled for a large-scale (100 MW_e) particle receiver system using expected emission rates based on previous testing and meteorological conditions for Albuquerque, New Mexico. Results showed that the expected emission rates yielded particle concentrations that were significantly less than either the pollution or inhalation metrics of 12 μg/m^3 (averaged annually) and 15 mg/m^3, respectively. Particle emission rates would have to increase by a factor of ~400 (~0.1 kg/s) to begin approaching the most stringent standards.

INTRODUCTION

High-temperature particle receivers are being developed in concentrating solar power (CSP) applications to provide heating and thermal storage for high-efficiency power cycles that require turbine inlet temperatures above 700 °C [1]. Particles can be used to store and convert solar energy for multiple applications including electricity production [1], process heat and manufacturing [2], and thermochemistry/fuels production [3]. For electricity production, the use of inert particles such as sintered bauxite or sand has significant advantages over the use of conventional molten nitrate salts, including greater range of operating temperatures (subzero to >1000 °C vs. ~200°C – 600 °C), low costs, low corrosion effects, and no need for air-tight seals [4]. Reactive particles such as ceria can be used in two-step reduction/oxidation processes to create synthetic fuels and hydrogen to supplant fossil fuels [5]. Heated particles can also be stored efficiently and inexpensively for long periods in low-cost storage bins for dispatchability and on-demand use [6]. Current challenges with particle-based CSP systems include reduction of heat and particle losses from the receiver and low particle-side heat transfer coefficients in the heat exchanger.

Previous research has focused primarily on the performance and operation of these particle-based systems. Few studies have evaluated the potential environmental impacts such as inhalation hazards and pollution from particles and fines emitted from the open aperture of a falling particle receiver. The purpose of the present work is to evaluate the particle emissions from particle receiver systems via modeling and on-sun tests and compare the resulting particle concentrations against applicable standards. Relevant protective standards include the U.S. National Institute for Occupational Safety and Health (NIOSH) particle inhalation metric of 15 mg/m^3 and the U.S. Environmental Protection Agency (EPA) particle pollution metric of 12 μg/m^3 (averaged annually).

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TESTING

In 2018, particle sampling instruments were deployed at the National Solar Thermal Test Facility (NSTTF) during on-sun field tests of Sandia's particle receiver to determine if small particles were being generated that can pose an inhalation hazard. A suite of particle sampling instruments was distributed around the receiver and tower to gather data on particle emissions. Different instruments were used to characterize both large (10 – 2000 microns) and small (<10 microns) particles (**FIGURE 1** and **FIGURE 2**). Results showed that while there were some recordable emissions during the tests, the measured particle concentrations were much lower than the NIOSH health standard of 15 mg/m^3 [7]. Additional details of the testing and results can be found in Ho et al. [7].

FIGURE 1. Images of the Malvern Spraytec used to evaluate large particle emissions (tens to hundreds of microns) at the NSTTF. The Spraytec was placed in an aerial lift to be positioned just beneath the aperture of the receiver [7].

FIGURE 2. Traditional volumetric air samplers were used to evaluate small particle emissions (submicron to micron) at the base and top of the tower at the NSTTF [7].

Due to wind effects, it was uncertain if the discrete locations of the sampling instruments were sufficient to capture emitted particle fines. Therefore, modeling of particle emissions and plume concentrations was performed to determine the location and shape of the particle plume relative to wind speed and direction.

MODELING APPROACH

Model Description

Two models were developed to simulate particle plume concentrations from the particle receiver. A detailed computational fluid dynamics (CFD) model was developed to simulate both large and small particle emissions and to evaluate plume shape as a function of wind speed. An EPA-recommended plume modeling software (AERMOD) was also used to simulate and evaluate averaged plume concentrations over longer periods of time for comparison to EPA standards. Benchmarking of the two models was performed.

Computational Fluid Dynamics Modeling

A computational fluid dynamics (CFD) model of the emission and dispersion of particles from Sandia's 1 MW_t particle receiver was developed using Solidworks Flow Simulation. The particle trajectories and plume concentration were modeled as a function of wind speed, wind direction, and particle emission rate. Two particle sizes were investigated: 350 microns (which is the initial, as-received nominal size for 40-70 mesh CARBO HSP ceramic particles) and ≤ 10 microns (for comparison to inhalation and pollution standards for particle fines that may be generated). Particle sizes on the order of 10 microns or less were found to be essentially buoyant and followed the flow lines of the wind velocity. Therefore, for comparison to EPA National Ambient Air Quality Standards (NAAQS) for particulate matter (PM) 2.5 and PM 10 (i.e., particles equal to or less than 2.5 and 10 microns, respectively), small particles were simulated as a gas having the same molecular weight (0.11 kg/mol), specific heat (1200 J/kg-K), and thermal conductivity (2 W/m-K) as the CARBO HSP particles. The dynamic viscosity was assumed to be the same as air. The aperture of the falling particle receiver was assumed to emit particle fines (<10 microns) at a rate estimated to be ~1e-5% of the particle mass flow rate for small particle generation, which was estimated from previous tests [7]. For a particle mass flow rate of 5 kg/s, which provides 1 MW_t of power with a ΔT of 200 °C and a specific heat of 1200 J/kg-K, the emission rate was calculated to be 5e-7 kg/s. The mass fraction of the particle emissions was assumed to be one so that only particles would be generated (and not air) from the aperture, which was located on top of the 61 m (200 ft) tall tower. The temperature of the particle gas emitted from the aperture was assumed to be 700 °C, which is approximately the average of the design temperatures of the particles entering and exiting the receiver.

AERMOD (EPA Particle Dispersion Modeling Software)

Additional modeling was performed using the EPA-recommended modeling software, the American Meteorological Society / EPA Regulatory Model (AERMOD), for a commercial-scale (100 MW_e) particle receiver system. AERMOD was designed to support the EPA regulatory programs and, as such, is considered the most appropriate model to perform air dispersion modeling analysis for continuous or intermittent emission sources.

AERMOD is a steady-state plume modeling software that is designed to model dispersion and deposition of six common air pollutants, designated as "criteria air pollutants" by the EPA; these pollutants are ozone (O_3), carbon monoxide (CO), lead (Pb), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter (PM). Particulates are the only pollutant emitted from the tower, so equations in AERMOD not pertaining to particulate dispersion and deposition were omitted in the analyses. The Appendix contains a description of the particle deposition model in AEROMOD. A description of all the equations governing AERMOD, as well as program development documents, can be found in the "Model Supporting Documents" section on the EPA's Air Quality Dispersion Modeling site.*

AERMOD requires specification of source parameters (size, pollutants emitted, emission temperature, emission rates, and aperture size) which are then analyzed in hourly increments using meteorological data provided by the user. These hourly increments are then averaged over user-requested time periods and can then be used in 3D visualization software to create a volumetric or isometric surface of the particle concentrations representative of the averaged time

* https://www.epa.gov/scram/air-quality-dispersion-modeling-preferred-and-recommended-models#aermod

periods. In addition to local meteorological data, AERMOD also considers the planetary atmospheric boundary layer(s) when calculating pollutant dispersion.

The mass fractions of the particles emitted in the two size ranges of PM 2.5 and PM 10 are assumed to be equal (50% each) for the AERMOD simulations. The emission source for a 100 MW_e falling-particle receiver is assumed to be a north-facing circular aperture (22.6 m in diameter; equivalent to a 20 m x 20 m square aperture) located 285 m above the ground. Particles with a density of 3,300 kg/m^3 are emitted from the aperture at a temperature of 700 °C with a mass flow rate of 2.8e-4 kg/s (~1 kg/hour). The mass flow rate of the emitted particles is based on an assumed flow rate of particles through the receiver of 2000 kg/s (to achieve 100 MW_e). Previous testing has estimated that the small particle generation rate (<10 microns in size) is 1.4e-5% of the total particle flow rate through the receiver.

The tower is assumed to be in a geologically flat area located near the NSTTF. The closest public receptor for evaluating the EPA standards was assumed to be located 1,500 m away (at the perimeter or "fence line" of the plant as required by EPA standards). For comparison, the heliostat field at the 110 MW_e molten-salt CSP plant (with 10 hours of storage) has a heliostat field that extends approximately 1,600 m from the tower. Peak ground-level particulate concentrations at various radial distances in the vicinity of the tower were also investigated to determine potential hazards to on-site workers.

Meteorological data was taken from the NSTTF site. This data reflected the hourly conditions of the site over a five-year window spanning from 2013 to 2017. This dataset was generated using data from the sitewide meteorological tower network at Sandia National Laboratories. The regional climate is dry and sunny, with an annual average precipitation of 20 cm (8 in) and an average of nearly 300 sunny days annually.

For this model a three-dimensional cartesian receptor grid was created centered around the tower. The grid was 3,000-meters north-south by 3,000-meters east-west by 500-meters vertically. Receptors were spaced every 100-meters circumferentially around the tower (at a radial distance of 1,500 m) and every 25-meters vertically at the nearest Cartesian coordinate. The grid was populated with over 20,000 discrete receptors at which concentrations were directly calculated.

Separate models were created to analyze the behavior of both the PM-2.5 emissions and the PM-10 emissions individually, then a final model was created for the purposes of analyzing the combined emissions simultaneously. This final model accounts for the varying particle sizes in the plume and their interactions and yields the concentrations for the total suspended particulates (TSP). The TSP may be different than the sum of the individually calculated PM-2.5 and PM-10 results due to particulate interactions.

Finally, a simulation was performed to calculate the maximum allowable particle emission rate that could be sustained before the concentrations were longer in compliance with the most stringent of federal and state standards. Between federal (NAAQS) and state (NMAAQS) standards the most stringent requirements necessitate that a source not cause the 24-hour average ground-level pollutant concentrations to exceed the following thresholds 35 $\mu g/m^3$ for PM 2.5 and 150 $\mu g/m^3$ for PM 10. Additionally, these standards necessitate that an annual average of ground-level PM 2.5 not exceed 12 $\mu g/m^3$.[†,‡] The maximum particle emissions rate was determined by running several iterations of the initial models until ground-based receptors returned a violation of any of the air quality standards.

MODELING RESULTS

Benchmarking (CFD vs. AERMOD)

A sample of the results of the CFD modeling of particle emissions from the existing particle receiver at the NSTTF are shown in **FIGURE 3**. For a west wind of 2 m/s (~5 mph), the steady-state results using the input parameters described earlier yield a plume that extends horizontally downstream from the aperture on top of the tower. The plume exhibits a slightly non-uniform shape due to the impact of the geometry of the tower and particle receiver on the wind, which creates a swirling pattern that extends slightly upward downstream of the tower. The extent of the plume with a maximum particle mass fraction of 1e-9 kg/kg (1 ppb) extends less than 100 m from the aperture. The maximum particle mass fraction of 1e-8 kg/kg (10 ppb), which corresponds to the EPA annual average concentration limit for PM 2.5 of 12 $\mu g/m^3$ under ambient air conditions, extends only ~20 m from the aperture. This indicates that the likelihood of exceeding the EPA metrics for a receptor located outside of the boundaries of the CSP plant are very low.

[†] U.S. EPA NAAQS Table: https://www.epa.gov/criteria-air-pollutants/naaqs-table
[‡] Albuquerque Bernalillo County: http://164.64.110.134/parts/title20/20.011.0008.html

Different wind speeds were simulated in the CFD model, and results showed that higher wind speeds diluted the particle concentrations. For example, for a 10 m/s west wind speed, the maximum particle concentration of 1e-9 kg/kg (1 ppb) extended only about 30 m downstream of the aperture, less than half the distance with a 2 m/s wind speed. In addition, different particle emission rates were simulated. Higher particle emissions from the aperture led to larger and more extensive plumes, which was expected. Finally, different wind directions were simulated, but the impact on the particle plume shape and concentrations was small relative to the impact from wind speed and particle emission rates.

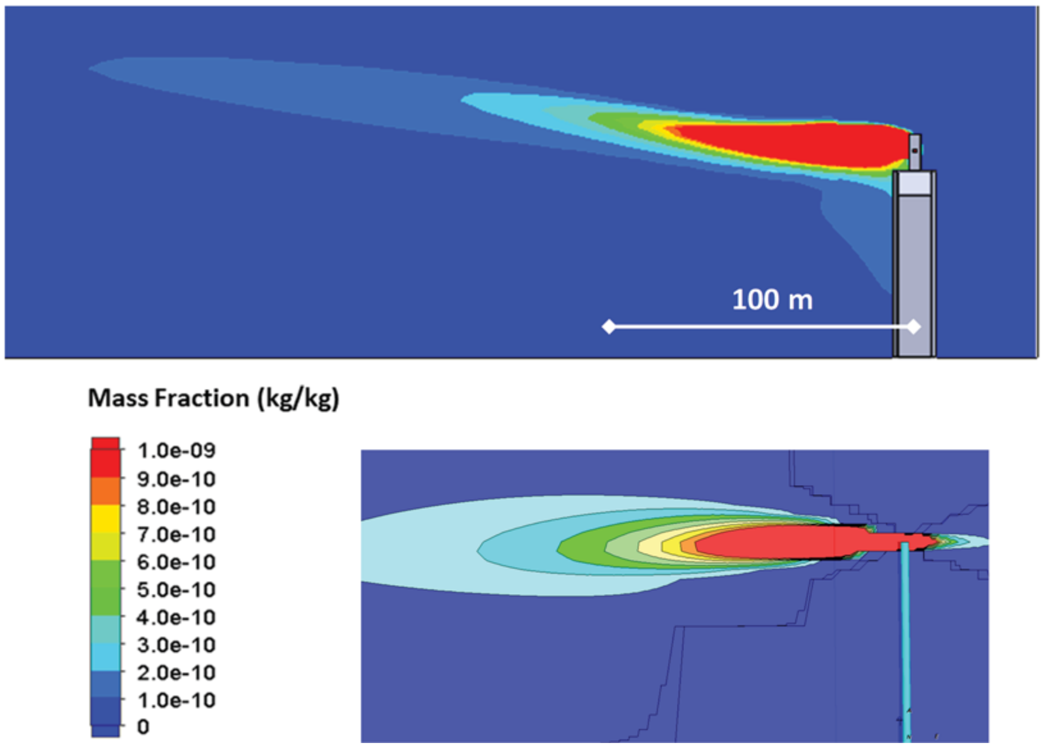

FIGURE 3. Simulated small particle (<10 μm) mass fractions in air with a west wind speed of 2 m/s using CFD (top) and AERMOD (bottom).

FIGURE 3 also shows the simulated particle concentrations from an equivalent AERMOD model of particle emissions from a particle receiver at the NSTTF. The same boundary conditions and properties were used in the AERMOD model for benchmarking purposes. Results show that the AERMOD model yields similar results to the CFD model. The particle plume extends horizontally downstream from the aperture with a 2 m/s west wind. The AERMOD plume is more symmetric about the horizontal plane because the impact of the tower and receiver geometry are not included in the AERMOD model. Also, the assumption of buoyant particles (for sizes < 10 μm) in the CFD model appears to be supported by the AERMOD dispersion model. A discrepancy between the CFD and AERMOD results was observed at different wind speeds. At higher wind speeds, AERMOD yielded larger particle plumes, which was counter to the dilution effect observed in the CFD results. At higher wind speeds, the extent of a plume with prescribed isopleths should be smaller if all other factors and boundary conditions are the same. This issue was raised with the developers of AERMOD, and investigations are ongoing.

Large Particle Emissions

FIGURE 4 shows the results of a CFD particle simulation in which 350 micron particles were emitted from the 1 MW_t particle receiver aperture ~70 m above ground at the NSTTF at a rate of 0.003 kg/s (the maximum rate estimated in past on-sun tests [8]). The simulation shows that these larger particles fall downward under the force of gravity and are not carried significantly in the presence of a relatively low wind speed of 2 m/s (~5 mph). This was further confirmed by analyzing the terminal velocity of these 350 μm particles. Assuming a spherical shape, the terminal velocity of individual particles was found to be ~2 m/s. This means that the average suspended time of these particles would be ~35 seconds from the receiver to ground level (and less than 3 minutes for a 300-m tall tower in a commercial-scale system), further confirming that they would not be carried a significant distance given normal terrestrial wind conditions.

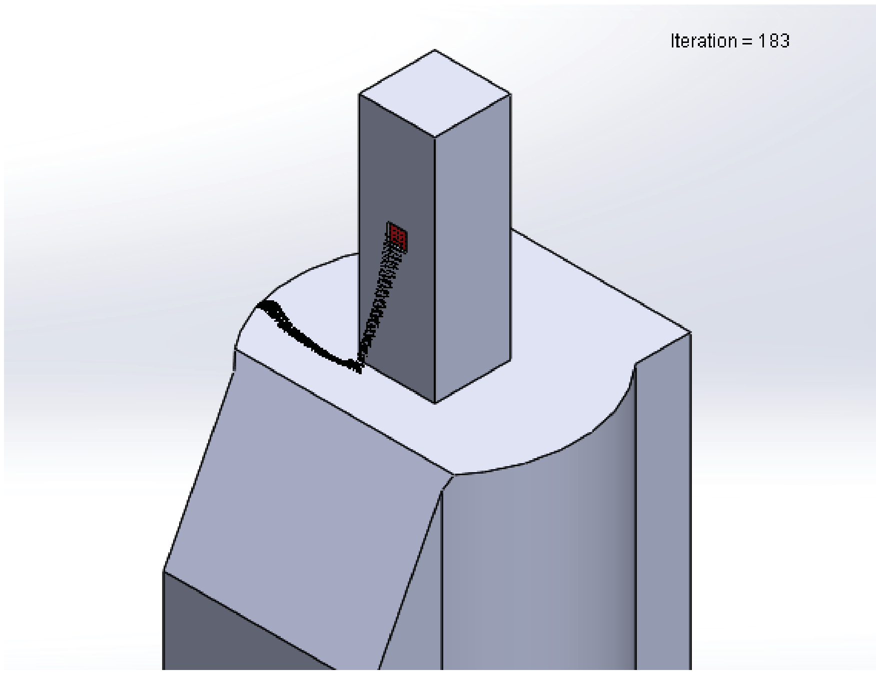

FIGURE 4. CFD simulation of 350 μm particles emitted from receiver aperture at the NSTTF (0.003 kg/s, 2 m/s west wind).

Small Particle Emissions

FIGURE 3 showed results of simulated small particle emissions from the 1 MW_t particle receiver at the NSTTF for both the CFD and AERMOD models at fixed wind speeds for purposes of benchmarking and comparison. In this section, results from the AERMOD model of a commercial-scale 100 MW_e ~300-m tall tower are presented using time-varying meteorological data. AERMOD reports time-averaged particle concentrations (e.g., 24 hours or annually) for comparison to the metrics prescribed in the NAAQS. **FIGURE 5** shows the 24-hour maximum PM-10 concentrations. The results reflect the maximum possible extent to which particulate concentrations may extend on any given day. The highlighted bubble in the center (red), indicates the maximum permissible ground level 24-hr average concentration of PM 2.5 (35 $\mu g/m^3$). This region of elevated particle concentrations barely extends vertically and horizontally beyond the aperture before it dissipates and does not risk reaching ground level.

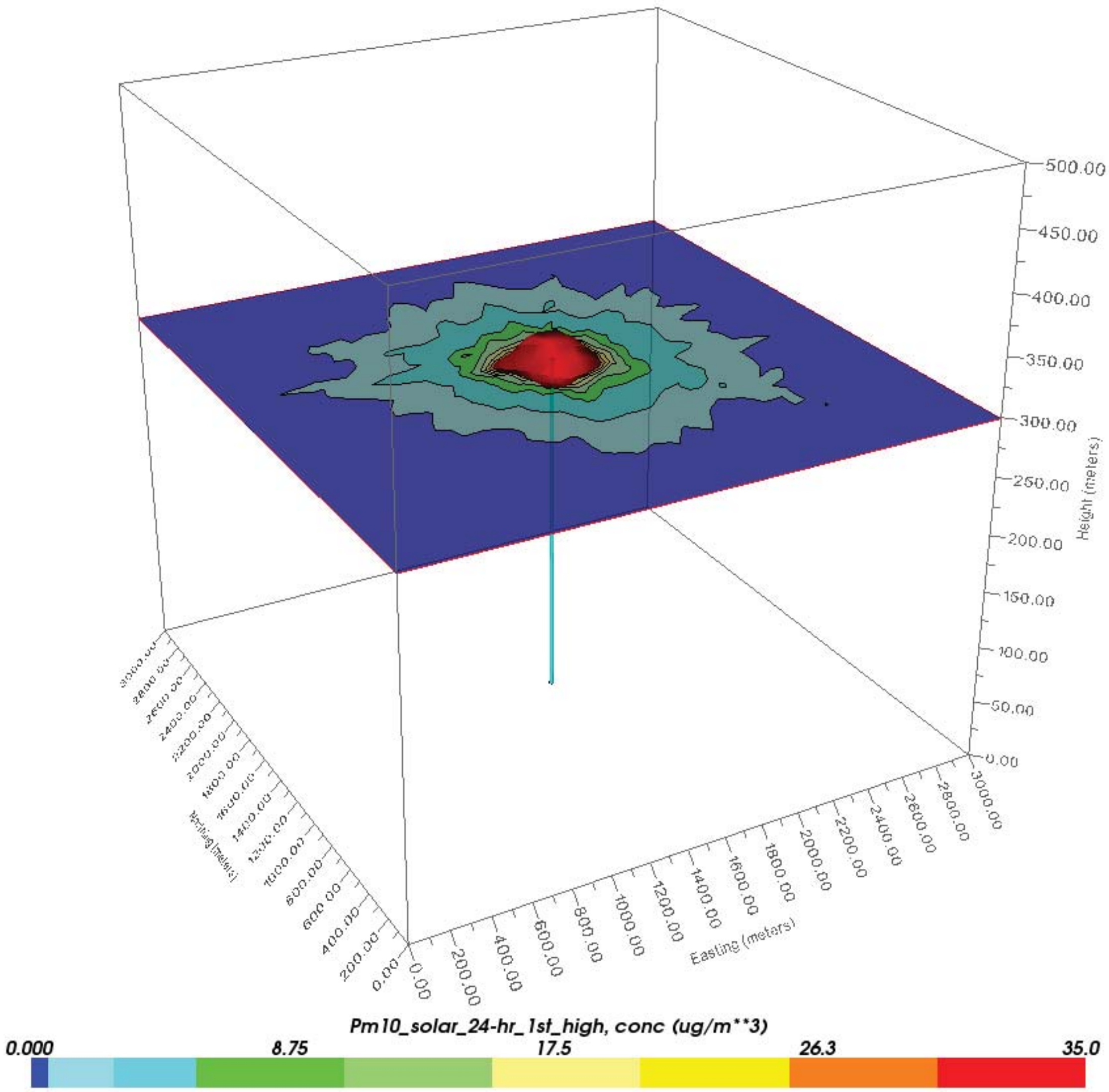

FIGURE 5. 24-hour maximum emission results from initial AERMOD modelling.

Results from the AERMOD model are summarized in **TABLE 1**, which presents the annual and 24-hour averaged particle concentrations of PM-2.5, PM-10, and total suspended particulates at the ground (for comparison to standards) and plume (peak). The results show that the simulated ground-level particle concentrations are all significantly less than the EPA and NM standards.

Since these initial simulations resulted in no violation of standards, additional modeling was performed to determine the particle emission rate that would violate the ambient air standards. The particle emission rate was continually increased until the ground-based particle concentrations approached the ambient air quality standards. The results of this secondary run are summarized in **TABLE 2**. Results showed that the particle emission rate could be increased by a factor of 400 before the ground-based particle concentrations began to approach the standards. This emission rate of ~0.11 kg/s or ~400 kg/hour corresponds to 5e-3% of the total particle mass flow rate through the receiver. It is interesting to note that Albrecht et al. estimated that a total particle loss rate of 1e-3% (including both large and small particles) was the maximum that could be sustained before a significant impact on the levelized cost of electricity was observed.

TABLE 1. Simulated small-particle plume concentration for a 100 MW_e plant using AERMOD with estimated emission rates from tests [7].

Modeled Parameter			Model Results ($\mu g/m^3$)	NAAQS and NMAAQS ($\mu g/m^3$)	Result
PM-2.5	Annual	Ground	0.006	12	PASS
		Plume	4.479		---
	24-hr	Ground	0.034	35	PASS
		Plume	117.2		---
PM-10	Annual	Ground	0.006	150	PASS
		Plume	4.544		---
	24-hr	Ground	0.043	150	PASS
		Plume	145.8		---
Total	Annual	Ground	0.012	12	PASS
		Plume	9.024		---
	24-hr	Ground	0.160	35	PASS
		Plume	290.4		---

TABLE 2. Simulated small-particle plume concentrations for a 100 MW_e plant using AERMOD with maximum emission rates.

Modeled Parameter			Model Results ($\mu g/m^3$)	NMAAQS ($\mu g/m^3$)	Result
PM-2.5	Annual	Ground	2.400	12	PASS
		Plume	1,792		---
	24-hr	Ground	13.50	35	PASS
		Plume	46,896		---
PM-10	Annual	Ground	2.431	150	PASS
		Plume	1818		---
	24-hr	Ground	17.20	150	PASS
		Plume	58,334		---
Total	Annual	Ground	4.831	12	PASS
		Plume	3,609		---
	24-hr	Ground	34.10	35	PASS
		Plume	116,118		---

Radius of Impact (ROI) Determination

The air-quality radius of impact (ROI) caused by the falling particle receiver can be determined using the EPA's Air Quality Index (AQI), an index for reporting air quality using 24-hr averages. Each criteria pollutant (for this model there is only PM 2.5 and PM 10) is standardized to a score ranging from 0 to 500 – the higher the score the greater the amount of pollutant in ambient air. A score greater than 500 is considered 'Beyond the AQI' and requires special remediation. **TABLE 3** briefly summarizes the applicable AQI standards for quick reference.

For the purposes of this report, the air-quality ROI is defined as the maximum radius at which ground level conditions would receive an AQI value of 51 or higher, resulting in "Moderate" or worse conditions. For these pollutants, this AQI value is equivalent to a 24-hr average ground level concentrations of 12.1 $\mu g/m^3$ for PM-2.5 and 55 $\mu g/m^3$ for PM-10, whichever occurs further from the tower. Ground-level impact models were run in the BREEZE 3D-Analyst and analyzed to create the ROI results. The ROI of the AERMOD model of the commercial-scale particle receiver, with empirically derived emission rates, is less than 300 m. The ROI of the simulation using the maximum allowable emission rate is 2,150-meters. In addition, the simulated peak ground-level concentrations of 0.0853 $\mu g/m^3$ (24-hour average) and 0.0121 $\mu g/m^3$ (annual average) in the vicinity near the tower using empirically derived emission rates were less than the allowable EPA standards of 35 $\mu g/m^3$ and 12 $\mu g/m^3$, respectively, which is relevant for on-site workers. Increasing the particle emission rate by a factor of 400 led to peak ground-level concentrations of 34.10 and 4.83 μg/m^3 for the 24-hour and annual averages, respectively.

TABLE 3. Air quality index (AQI) summary.*

Ambient 24-hr Average Concentrations (μg/m^3)		AQI Value	Level of Health Concern
PM-2.5	PM-10		
0.0 - 12.0	0 - 54	0 - 50	Good
12.1 - 35.4	55 - 154	51 - 100	Moderate
35.5 - 55.4	155 - 254	101 - 150	Unhealthy for Sensitive or At-Risk Groups
55.5 - 150.4	255 - 354	151 - 200	Unhealthy
150.5 - 250.4	355 - 424	201 - 300	Very Unhealthy
250.5 - 500.4	425 - 604	301 - 500	Hazardous
≥ 500.5	≥ 605	---	Extremely Hazardous

*https://www.airnow.gov/index.cfm?action=aqibasics.aqi

CONCLUSIONS

Testing and modeling have been performed to evaluate potential inhalation and pollution hazards associated with particle emissions from a falling particle receiver. Previous on-sun tests revealed that measured particle concentrations near the tower were significantly lower than the NIOSH standards of 15 mg/m^3 for inhalation risks. However, modeling has revealed that collection of small PM-2.5 and PM-10 particulates may be difficult due to their buoyant nature and ability to be carried large distances by wind. Nevertheless, both CFD modeling and the use of EPA's AERMOD dispersion model showed that exceedance of EPA standards for 24-hour and annually averaged ground-based concentrations was highly unlikely using estimated small-particle emission rates from previous tests. The particle emission rate had to be increased by a factor of 400, to 1e-3% of the total particle mass flow through the receiver, to approach ambient air quality limits for PM 2.5 and PM 10. The radius of impact causing an air quality index of moderate health concern was found to not extend beyond the boundaries of the plant. For larger particles (~350 μm), modeling results showed that the particles would settle to the ground rapidly due to gravity.

CFD simulations showed that wind speed and particle emission rates had more impact on the particle plume shape and size than the wind direction. Comparisons between the AERMOD and CFD simulations showed that the AERMOD model captured the salient shape and extent of the particle plume at a wind speed of 2 m/s. However, at higher wind speeds, results from AERMOD showed a larger particle plume, which was opposite the results from the CFD modeling results that showed a smaller particle plume (with prescribed isopleths) due to dilution from the wind.

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APPENDIX – AERMOD PARTICLE DEPOSITION EQUATIONS

The primary mechanism of removing airborne particulate matter (PM) from the atmosphere is through a process known as deposition, in which the PM falls to the earth due to either its own weight or other atmospheric phenomena. AERMOD makes use of both dry and wet deposition algorithms. Dry deposition is a measure of the particles simply falling to the ground over time. Factors include wind speed and direction and particulate size and concentration. Wet deposition accounts for precipitation and is a measure of water removing suspended particulate matter from the atmosphere. AERMOD makes use of the following equations to calculate particulate deposition:

$$F_d = \chi_d * V_{dp} \tag{1}$$

Where F_d is the rate of dry deposition flux (μg/m^2-s), χ_d is the concentration of particulate matter (μg/m^3) at a reference height (z_r), and V_{dp} is the particle deposition velocity (m/s), which is calculated as shown below:

$$V_{dp} = \frac{1}{R_a + R_p + R_a R_p V_g} + V_g \tag{2}$$

Where R_a is the aerodynamic resistance of the particles in (s/m), R_p is the quasilaminar sublayer resistance (s/m), which is a measure of the resistance to movement of the thin layer of air which is in direct contact with the particulate surface, and V_g is the gravitational settling velocity for the particles (m/s). All of the values used in calculating V_{dp} make use of both particle data (diameter and density) as well as the meteorological data provided to the program in order to account for air speed, temperature, and ambient pressure. Finally, V_g is calculated using the density and diameter of the particle as well as known parameters for ambient air as follows:

$$V_g = \frac{(\rho_p - \rho_A) * g * d_p^2 * c_2}{18 * \mu} S_{CF} \tag{3}$$

Where ρ_p and ρ_A are the densities (g/cm^3) of the particles and the air, respectively, g is the gravitational acceleration constant (9.81 m/s^2), d_p is the particulate diameter (μm), c_2 is a conversion factor between cm^2 and μm^2, μ is the absolute viscosity of air (g/cm-s), and S_{CF} is a dimensionless slip correction factor, which has an inverse dependence on particle diameter. It is worth noting that for particles larger than 1 micron in diameter the deposition is dominated by the gravitational settling term.

Wet deposition flux is calculated hourly and summed over the period to obtain total flux. The following equation is used to calculate wet deposition when the meteorological file indicates there is precipitation:

$$F_w = 10^{-3} * \chi_{pc} * W_p * r \tag{4}$$

Where F_w is the rate of wet deposition flux ($\mu g/m^2$-s), χ_{pc} is the average concentration ($\mu g/m^3$) of particulate matter in the vertical column in which there is precipitation occurring, W_p is the dimensionless particle washout coefficient, which is inversely dependent on the size of the raindrops and directly dependent on the frequency of collision between raindrops and particulate matter. Finally, r is the precipitation rate (mm/hr) provided by the meteorological data file, which is converted to m/hr by the 10^{-3} conversion factor in the equation.