# Cardinal Plant Modeling Parameterization of Unit 3 Cooling Tower Discharge and Emissions Input Development

In the original permit modeling for the switching of the discharge from the Cardinal Plant Unit 3 FGD System from a new stack to the European style of discharging FGD exhaust through a natural draft cooling tower it was determined that treating the total discharge as a stack type source was not a suitable way to parameterize the discharge and achieve reasonable model performance[1] with either AERMOD or CALPUFF. Such analyses resulted in widespread fumigation of the area with modeled concentrations being in the tens of thousands of micrograms over wide areas. This resulted in the use of CALPUFF and treating the cooling tower as a series of line sources with both a core set of line sources and two line sources covering the entire diameter of the cooling tower. This scheme, which was developed in an iterative fashion, ultimately proved successful in achieving believable results.

At the beginning of the SIP Development process a single simulation treating the cooling tower discharge as a stack was attempted with the then current regulatory version of AERMOD (13350) to determine if the problems with AERMOD found in the 2007/2008 time frame were still present when an on-site meteorologic dataset was used. This test simulation, based on 2013 meteorologic data from the Cardinal monitoring network and actual Cardinal Plant operating data, confirmed the unacceptable behavior was still present in the modeling system with the peak modeled receptor generating a value of 20,375 ug/m$^3$ and wide spread areas of the modeling domain showing concentrations greater than 10,000 ug/m$^3$. Additionally, the results of this simulation also significantly over predicted all Cardinal Plant Network monitors except the Highway 19 monitor as shown in Table 1. Since it was not desired to use CALPUFF for the SIP modeling due to time constraints in the SIP Development process, the decision was made to try to adapt the method developed by David Long of American Electric Power Service Corporation and initially presented at the AWMA Annual Conference in 2013[1] to handle the hourly operation of the cooling tower discharge being used.

**Table 1. AERMOD Results for test simulation treating the Unit 3 Cooling Tower as single stack at the Cardinal Plant Network Ambient Monitors.**

| Monitor | Monitor 2013 Annual Design Value ug/m$^3$ | Modeled 2013 Design Value without Background ug/m$^3$ | Percent Difference between Modeled and Monitored Values |
|---|---|---|---|
| **Trailer Sales** | **55.0** | **193.4** | **251.6** |
| **Unit 3** | **62.9** | **273.0** | **334.0** |

| | | | |
|---|---|---|---|
| **Storage Site** | **86.5** | **142.8** | **65.1** |
| **Highway 19** | **136.3** | **135.0** | **1.0** |

During the testing phase of the development effort, Cardinal Units 1 and 2 were inserted into the model on an hour by hour basis using flue gas flow, temperature, and emission values generated by the Part 75 Continuous Emission Monitors (CEMS) located on the individual flues exiting through a traditional stack type discharge. Unit outages and low load operation were included in this dataset. In the final simulation discussed in the SIP Document, the inputs used for Units 1 and 2 were based on the CEMS Data but used a flat approach where all hours of operation greater than 580 MW on each unit were collected and the 90$^{th}$ percentile value of gas flow, temperature, and emissions were determined. This resulted in the 90$^{th}$ percentile values obtained being based on 3955 hours of operation for Unit 1 and 4020 hours for Unit 2 with the obtained values applied over the entire 8760 hours.

The FGD Discharge from Cardinal Unit 3, however, is very different. The FGD Discharge from Unit 3 is routed to the 424 foot tall natural draft cooling tower that serves the unit. The FGD discharge duct from the FGD System is routed into the cooling tower and discharges approximately 30 feet above the top of the counter flow fill. The parameterization of the discharge for Unit 3 must include the air flow from the cooling tower as well as the flue gas processed through the FGD System. As the work has unfolded, the cooling tower parameterization for use with AERMOD has evolved from being analogous to the techniques as used for the permit modeling performed using the CALPUFF model with BLP algorithms in the 2007 – 2008 period to a final methodology using significantly improved cooling tower parameterization data at a one hour resolution and increasing the area considered the primary zone (core) of flue gas from 50% of the exit diameter to 75% of the exit diameter. In its final form, the parameterization supports air quality model performance that is within USEPA model performance guidance and also demonstrates that the primary impact area of the emissions discharged through the cooling tower remains in the near field to the tower. The following sections detail the evolution of the formulation for each of the three principal cases evaluated.

**UNIT 3 COMBINED COOLING TOWER AND FGD DISCHARGE PARAMETERIZATION DEVELOPMENT**

**<u>INITIAL CASE</u>**

This case was designed to convert the original permit modeling characterization used in CALPUFF in the permit modeling study into an hourly form for use in SIP Development. This case used the air flow rate from the original cross flow cooling tower design of

26,000,000 acfm and the exit air temperature for the air flowing through the cooling tower that was varied on a month by month basis as shown in Table 2 in an effort to better represent the buoyancy of the plume from the cooling tower based on the ambient temperatures acting on the tower. This value was then adjusted on an hour by hour basis for the mixing effects of the flue gas temperature and flow from the FGD as measured by the CEMS with the air flow through the cooling tower to generate a final exit temperature of the total flow leaving the cooling tower under the assumption of complete mixing of the two streams prior to their exiting the cooling tower.

**Table 2. Monthly temperatures used in parameterizing the cooling tower air flows (°K).**

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Temp Used °K** | 291.5 | 294.3 | 297.0 | 299.8 | 302.6 | 305.4 | 308.2 | 308.2 | 302.6 | 299.8 | 294.3 | 294.3 |

The original CALPUFF based scheme assumed two full diameter line plumes and four half diameter line plumes to achieve what was at the time believed to be adequate model performance[2]. The emissions were distributed 20% of the hourly emissions value to the entire diameter and the remaining 80% was assigned to the half diameter lines (core portion of the tower). These line plumes were recreated for use in AERMOD using the techniques described by Long[3] as two elevated area sources, one having the diameter of the entire exit diameter of the cooling tower and the other having the diameter of half of the exit diameter of the cooling tower.

The buoyancy flux was calculated on an hourly basis using Equation 1 shown below:

$$F' = \frac{gLW_m Aw(T_s - T_m)}{T_s}$$

where

F' = The buoyance flux ($m^4/s^3$)
g = gravitational constant (9.81 m/sec $^2$)
L = Length of the Line Source (m) – 27.125 meters constant (1/2 Exit Diameter)
$W_m$ = Width of the Line Source (m) – 13.0 meters constant
A = Area Adjustment Factor – 1.0 for full tower, 0.244 for initial case core, 0.5625 improved case core
w = Exit Velocity (m/sec)
$T_s$ = Combined Flows Temperature (K)
$T_m$ = Ambient Temperature (K)

As previously discussed, the stack temperature is based on the assumption of uniform mixing of all air and gas flowing through the cooling tower and is based on a volume weighted scheme as shown in Equation 2:

$$T_s = \frac{(T_{fg} * V_{fg}) + (T_{af} * V_{af})}{(V_{fg} + V_{af})}$$

Where

$T_{fg}$ = Temperature of the Flue Gas (K)
$T_{af}$ = Temperature of the Air Flow in the Cooling Tower (K)
$V_{fg}$ = Volumetric Flow of Flue Gas (acfm)
$V_{af}$ = Volumetric Flow of Air in Cooling Tower (acfm)

The final hourly volume source height for the core volume and the total tower volume sources was then computed using the buoyancy flux calculated above for each volume source for every hour as shown in Equation 3 as follows:

$$Z = \left(\sqrt{\frac{F'}{2\beta L U_s^3}}\right) * (34.49 * F'^{0.4}) + H_s$$

where,

β = entrainment parameter – constant 0.6
U = measured wind speed at Dam Site (m/sec)
34.49 = Constant from BLP Manual Equation 2-38[4]
$H_s$ = Height of Discharge (m)

The plume elevation was not capped, allowing the plume to rise infinitely until it was either driven over by wind speed in the model or the plume ran out of buoyant energy. This assumption results in some very high calculated plume heights during stable low wind speed conditions. This is not a major concern as the conditions resulting in peak concentrations occur during periods of elevated wind speed, which does result in modest plume elevations being calculated.

It should be noted that model performance at the monitors sited to capture the peak cooling tower FGD discharge impacts, the Unit 3 and Trailer Sales Monitors, along with the Storage Site Monitor, exhibited their maximum over prediction in this case as shown in Figures 1- 3 and Tables 3 - 5 in the monitor specific discussion of the results.. Model performance with this case did not meet USEPA guidance values[5] and other useful metrics for determining adequate model performance at the Unit 3 and Trailer Sales Site Monitors, but did meet all metrics at the Storage Site and the Highway 19 Monitors. The Storage Site Monitor was sited to examine the impacts of channeling on the distance scale that would still see significant impacts from the Unit 3 Cooling Tower Discharge. The Highway 19 Monitor had been sited to measure impacts primarily from

Units 1 and 2 based on the Unit 3 Permit Modeling[6] and analysis of the monitor data shows minimal impact from the operation of Unit 3 since the FGD system was placed in service in 2012, so the apparent lack of modeled impact from Unit 3 at this monitor was not surprising.

## IMPROVED COOLING TOWER PARAMETERIZATION CASE

Since AERMOD was significantly over predicting impacts at the monitors sited primarily to examine Unit 3 impacts, an investigation was undertaken to determine the likely cause of the poor model performance at these locations.

After examining the data used in the analysis, a question was raised about other changes that may have been made in the cooling tower itself in conjunction with the FGD discharge installation and the possible benefits from improving the estimation of air temperatures above the fill. During this phase it was discovered that a major design change in the cooling tower was made in conjunction with the FGD Discharge Project. This change converted the cooling tower from a cross flow design to a counter flow design, reducing the air flow through the tower from 26,000,000 acfm at design conditions to 17,000,000 acfm. The design document and an examination of the operational data available from the plant monitoring system also suggested that the cooling tower was much more dynamic system than a monthly above fill temperature estimate reflected, so an effort was undertaken to generate an improved estimator of the air temperature above the fill on an hourly basis from the available operational data.

After study of the likely heat transfer from the circulating water to air flow, a reasonable general estimator of the air temperature appeared to be generated by taking the circulating water temperature to the cooling tower and subtracting 6 °F from that temperature. In consultations with American Electric Power Service Corporation Mechanical Engineering representatives this was considered a reasonable approximation if one did not want to do more elaborate thermodynamic and heat transfer calculations on the cooling tower to obtain an even better estimate of the air temperature above the fill.

This 6 °F case was viewed as a reasonable holding for all conditions except extended subfreezing conditions. Under extended subfreezing conditions, it is necessary to direct a portion of the circulating water coming from the unit directly into the cooling tower basin to prevent the cooling tower basin temperature from approaching freezing, resulting in a reduction in the air temperatures observed above the fill. However, without performing detailed hour by hour cooling tower performance calculations for this case, the exact impact on the above fill temperature is difficult to estimate. Since this condition is not easily evaluated and only occurs during random periods in the winter, it was decided to use the hourly circulating water temperature to the cooling tower minus

6 °F as an estimator or the air temperature above the fill for all operating hours in the year. This value was then substituted into Equation 2 for $T_{af}$ on an hour by hour basis along with the change in air flow ($V_{af}$) from 26,000,000 acfm to 17,000,000 acfm and the computations were repeated for each operating hour during the year.

When this improved cooling tower parameterization was applied to the Unit 3 inputs used in AERMOD, it resulted in a significant improvement in model performance at the Unit 3 and Trailer Sales Monitoring Sites. Some improvement in model performance was observed at the Storage Site monitor location, and little change was observed at the Highway 19 Monitor, suggesting that the main impacts observed from Unit 3 were held to a small area directly around Unit 3 as had been the case noted in the modeling study from the cooling tower FGD discharge modification and were being captured by the Unit 3 and Trailer Sales Monitors as planned.

## CHANGED CORE SIZE PLUS IMPROVED COOLING TOWER PARAMETERS CASE

Following the evaluation of the improved cooling tower parameterization case, it remained apparent that there was still more possibility for improvement in the cooling tower discharge characterization. However, it did not appear that much further improvement was readily available through the cooling tower parameterization itself without going into the far more elaborate cooling tower performance calculations mentioned previously. The portion of the exhaust considered the "core" portion of the tower that carried 80% of the emission loading was the one main factor that had not been examined since the parameterization work had been started.

It was known from the work done to permit the cooling tower discharge that a single full diameter parameterization did not result in satisfactory model performance, even when multiple line sources were used. However, the evaluation at that time of permitting did not exhaustively look at various core sizes due to time constraints. Based on best engineering judgment at the time of the permit modeling, a core size of 50% of the diameter of the discharge was selected and the model performance was considered adequate based on qualitative judgment since no model performance studies for the case of a natural draft cooling tower based discharge being modeled with CALPUFF could be identified and ambient data in the near field was not available to aid in model performance evaluation from any site in the world.

The core percentage was revisited and the original source material used to select the 50% core value was reevaluated. After reexamining the source of the original estimate, a value of 75% of the exit diameter for the core area was selected. This changed the value of the area adjustment factor from 0.244 for the 50% of diameter case to 0.5625 for the 75% of the exit diameter case. When this change was made, all of the operating parameter improvements described in the previous section were retained and a new set of hourly input parameters were generated. When the AERMOD results were evaluated, the model performance was further improved at the Unit 3 and Trailer Sales sites (Figures 1 and 2), slightly improved at the Storage Site (Figure 3), and remained essentially unchanged at the Highway 19 Site (Figure 4).

## MONITOR BY MONITOR ANALYSIS OF DEVELOPMENT CASES

The following sections summarize the result of model vs monitor comparison data for the three main cases described above by monitor. All data shown is based on 2013 calendar year analyses using meteorology primarily sourced from the Cardinal Monitoring Network Dam Meteorology Site (39-081-0019). All modeled values have a background of 8.1 ppb (21.17 ug/m$^3$) included in the modeled values used in the plots and tables. In addition, all negative values of Percent Differences, Bias, and Fractional Bias shown in Tables 3 – 6 indicate model over prediction. The monitoring sites in the Cardinal Plant $SO_2$ network were selected following the completion of the Unit 3 FGD Permit Modeling in conjunction with Ohio EPA to allow a thorough evaluation of the CALPUFF modeling platform used in the permit modeling.

### <u>UNIT 3 MONITOR (No AQS ID Number Assigned)</u>

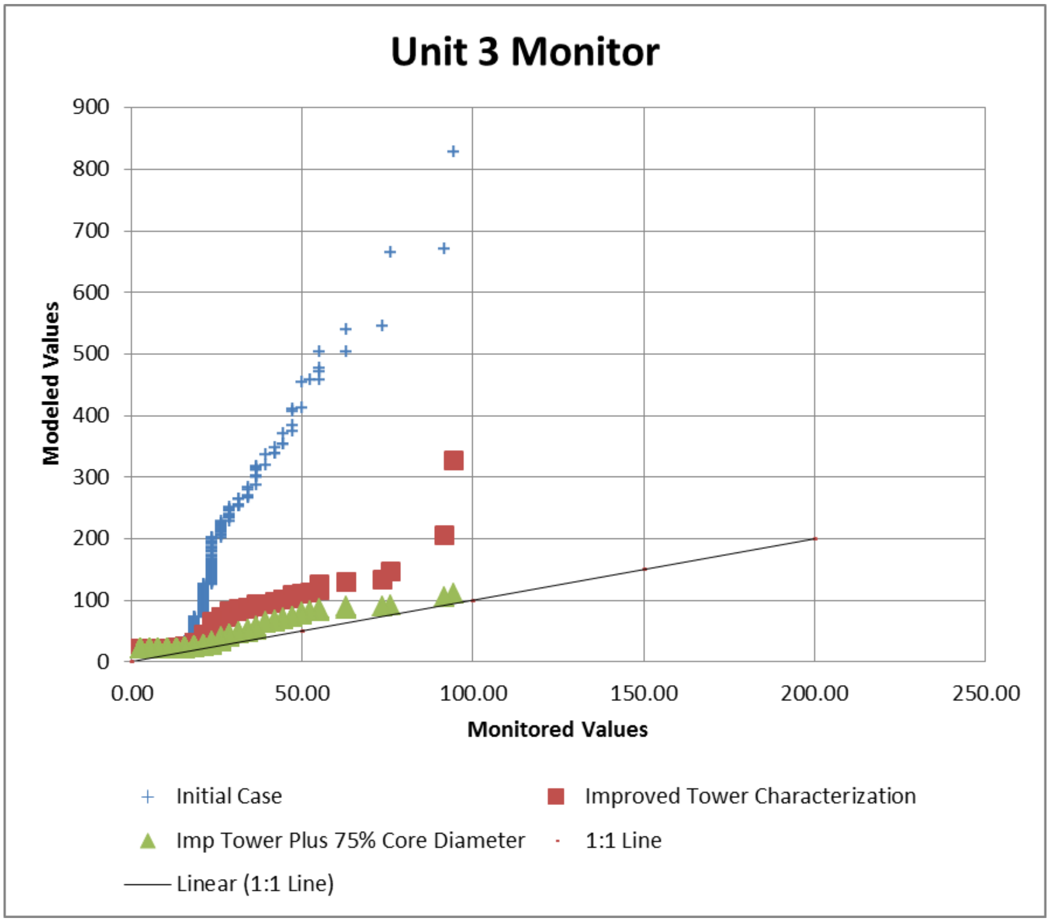
The Unit 3 $SO_2$ Monitor is located on the plant side of the main security fence near the railroad tracks on the west side of the plant site just north of Unit 3 and was classified by Ohio EPA as an industrial monitor that was not monitoring ambient air. This site was selected due to available resources necessary to support an ambient monitor, the need to avoid placing the monitor on railroad property and/or right of way, and its proximity to the modeled 3-Hour High Second High modeled value from the Unit 3 FGD permit modeling[7]. This monitor is located 0.37 kilometers from the Unit 3 Cooling Tower at a bearing of 189.7 degrees and would potentially be subject to downwash of the plume from the cooling tower discharge flowing over the top of the Unit 3 steam generator building and 1.27 kilometers from the Unit 1 and 2 stack at a bearing of 43.0 degrees.

Analysis of the modeled and monitored results at this site shows that elevated concentrations measured here are primarily attributable to impacts from Unit 3. This is demonstrated by the direct improvements in both the Q-Q plot in Figure 1 and in the statistical values in Table 3 as the parameterization of the cooling tower discharge was changed. In all cases the model over predicts the monitored values with the initial case failing to meet USEPA guidance for determining adequate model performance. However, the statistical measures for both of the improved parameterization cases meet USEPA guidelines for demonstrating adequate model performance, with the case with the improved cooling tower parameterization and the 75% of diameter of the cooling tower being considered the tower core showing the best overall performance of the different options.

**Table 3. Monitor vs Modeled value statistics for 2013 data for the Unit 3 Monitor Site (values in ug/m$^3$)**

| Parameter | Initial Case | Improved Cooling Tower Parameterization Case | Improved Cooling Tower Parameterization Plus 75% Core Size Case |
|---|---|---|---|
| **Monitored Peak** | 94.4 | 94.4 | 94.4 |
| **Modeled Peak** | 826.3 | 326.9 | 111.4 |
| **Percent Difference in Peaks (Model vs Monitor)** | 775.3 | 246.3 | 18.0 |
| **Monitored Design Value** | 62.9 | 62.9 | 62.9 |
| **Modeled Design Value** | 544.1 | 130.6 | 90.5 |
| **Percent Difference in Design Values (Model vs Monitor)** | -765.0 | -107.6 | -43.9 |
| **Paired Average Bias** | -1.12 | -1.10 | -1.08 |
| **Top 25 Monitored Values Average** | 54.4 | 54.4 | 54.4 |
| **Top 25 Modeled Values Average** | 450.8 | 123.7 | 79.3 |
| **Percent Difference in Top 25 Averages** | -728.7 | -127.4 | -45.8 |
| **Top 25 Values Unpaired Fractional Bias** | -1.56 | -0.78 | -0.37 |
| **Top 25 Values Average Unpaired Fractional Biases** | -1.57 | -0.76 | -0.39 |
| **Top 25 Values Standard Deviation of the Unpaired Fractional Biases** | 0.02 | 0.08 | 0.10 |

**Figure 1. Q-Q Plot of the three cases evaluated for the Unit 3 Monitor.**




## TRAILER SALES SITE MONITOR (Site ID 54-009-6000)

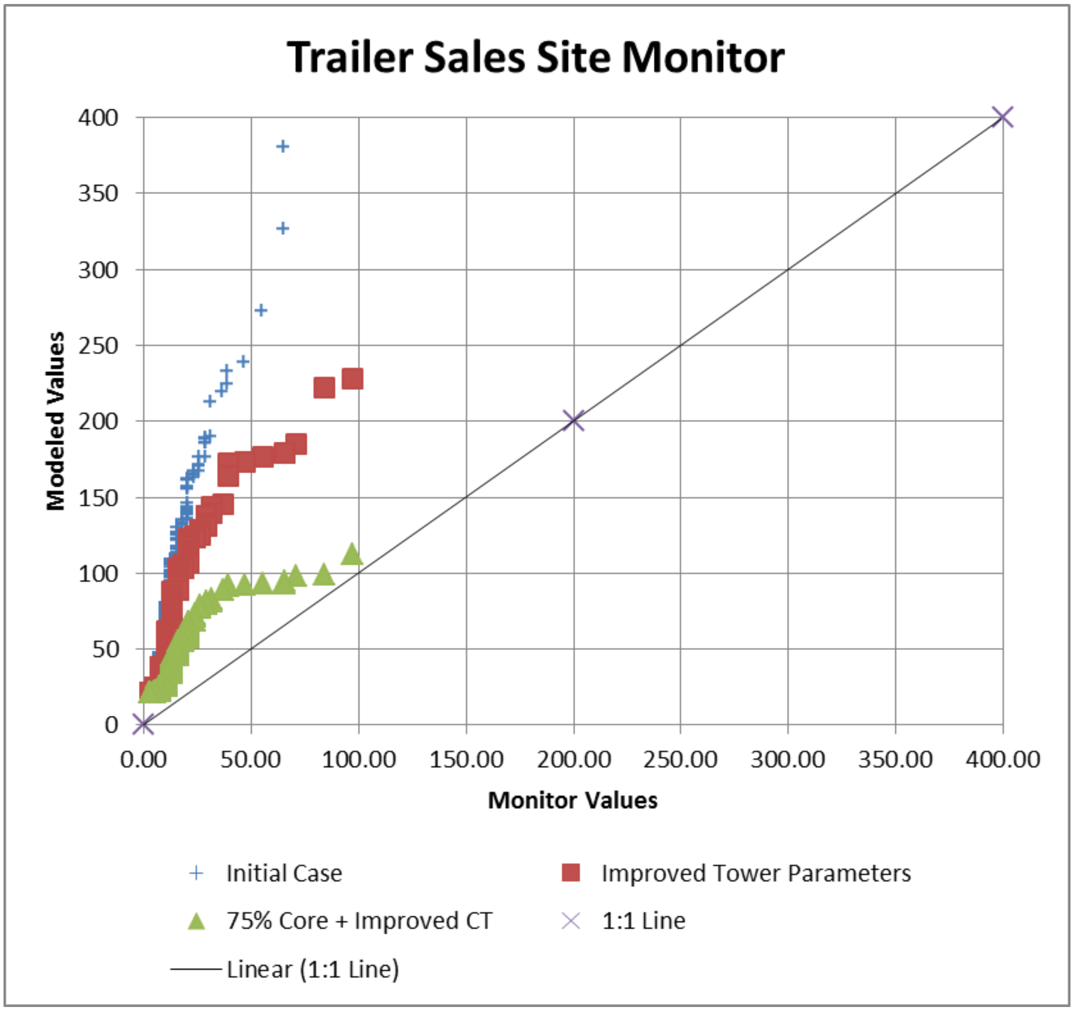
This monitor was sited based on the location of the 24-Hour High Second High receptor from the Unit 3 FGD Permit Modeling[8]. The actual modeled receptor is located in the navigation channel of the Ohio River and this proved to be the nearest location to the receptor location that met USEPA siting requirements for placing an ambient monitor. This monitor is located 0.65 kilometers at a bearing of 271.9 degrees from the Unit 3 Cooling Tower and 1.35 kilometers from the Units 1 and 2 Stack at a bearing of 12.0 degrees. In addition to an $SO_2$ Monitor, this site also contains a 10-meter wind speed and direction sensor, 2-meter temperature sensor, and a vertical wind speed sensor, along with reporting wind direction and vertical velocity standard deviation.

The modeling results in Table 4 show that the Initial and the Improved Cooling Tower Parameterization Cases do not meet USEPA guidance for adequate model performance at this monitor, even though there is a large improvement in model performance moving from the Initial Case to the Improved Cooling Tower Case. However, when the 75% core size adjustment is added to the evaluation combined with the Improved Cooling Tower Parameterization, adequate statistical model performance is demonstrated as shown in Table 4. This conclusion is supported by the results shown in the Q-Q Plot in Figure 2.

**Table 4. Monitor vs Modeled value statistics for 2013 data for the Trailer Sales Monitor Site (values in ug/m$^3$)**

| Parameter | Initial Case | Improved Cooling Tower Parameterization Case | Improved Cooling Tower Parameterization Plus 75% Core Size Case |
|---|---|---|---|
| **Monitored Peak** | 97.0 | 97.0 | 97.0 |
| **Modeled Peak** | 739.7 | 228.2 | 112.3 |
| **Percent Difference in Peaks** | -662.6 | -135.3 | -15.8 |
| **Monitored Design Value** | 55.0 | 55.0 | 55.0 |
| **Modeled Design Value** | 272.8 | 179.6 | 93.5 |
| **Percent Difference in Design Values** | -396.0 | -226.6 | -70.0 |
| **Paired Average Bias** | -1.36 | -1.35 | -1.33 |
| **Top 25 Monitored Values Average** | 40.3 | 40.3 | 40.3 |
| **Top 25 Modeled Values Average** | 245.6 | 151.4 | 79.3 |
| **Percent Difference in Top 25 Averages** | -509.4 | -275.7 | -96.8 |
| **Top 25 Values Unpaired Fractional Bias** | -1.44 | -1.16 | -0.71 |
| **Top 25 Values Average Unpaired Fractional Biases** | -1.44 | -1.20 | -0.78 |
| **Top 25 Values Standard Deviation of the Unpaired Fractional Biases** | 0.06 | 0.17 | 0.28 |

**Figure 2. Q-Q Plot of the three cases evaluated for the Trailer Sales Site Monitor.**




## STORAGE SITE MONITOR (Site ID 39-081-0020)

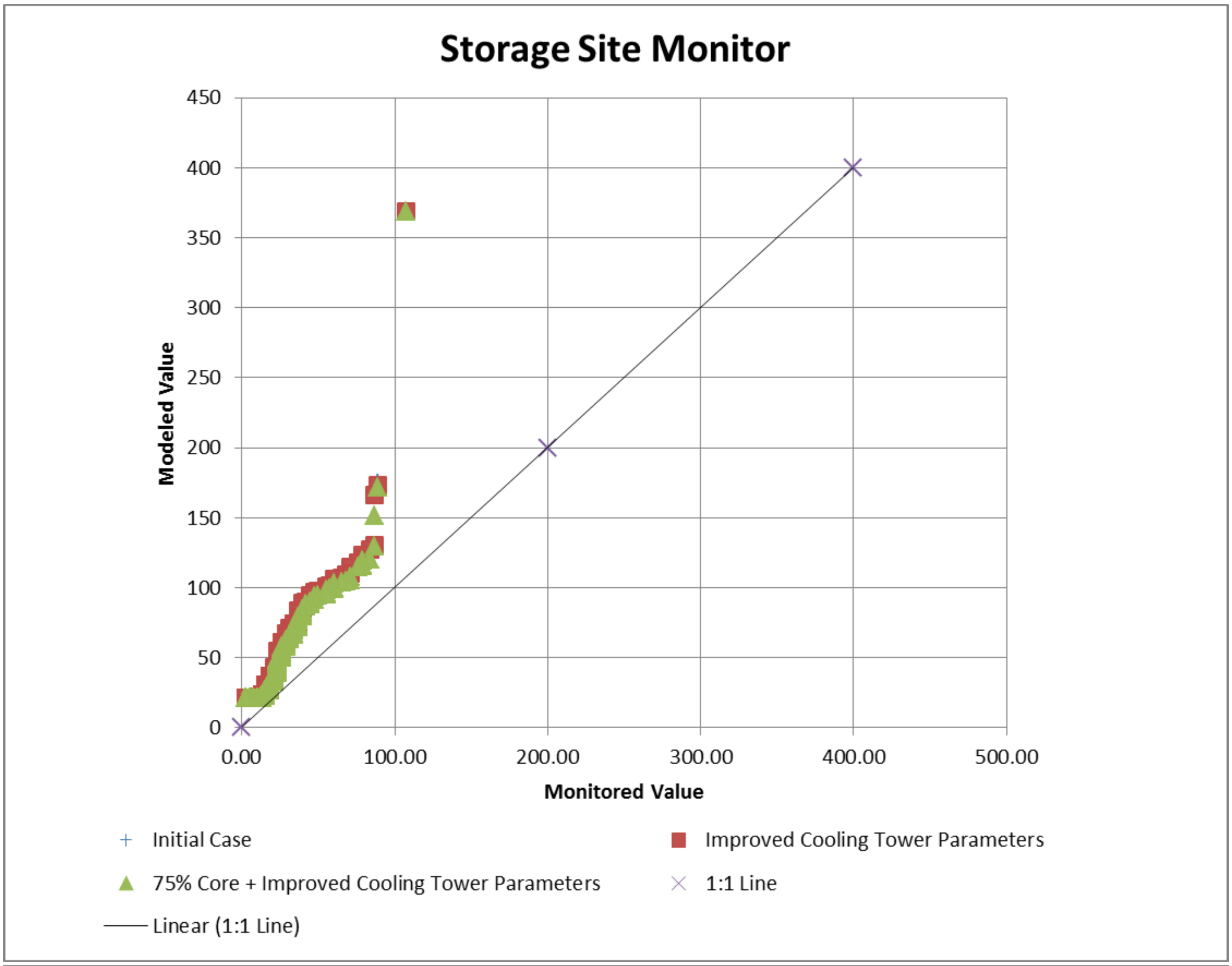
The storage site $SO_2$ monitor was located at an existing Cardinal Plant monitoring site as a matter of convenience. It was expected that this location would be a reasonable site to evaluate the Unit 3 downwind impacts. In addition to the $SO_2$ Monitor, the site also measures 10 meter wind speed and direction, 2 meter temperature, and reports wind direction standard deviation as part of the $SO_2$ study. This monitor is 2.53 kilometers from the Unit 3 Cooling Tower at a bearing of 216.8 degrees and 0.94 kilometers from the Units 1 and 2 stack at a bearing of 218.1 degrees.

In evaluating the results from this site, it quickly becomes apparent that this monitor is nearly out of the zone of significant influence for Unit 3. The statistical metrics shown in Table 4 are relatively insensitive to changes in the parameterization of the Unit 3 FGD Discharge and meet USEPA guidance metrics for acceptable model performance in all cases examined. This suggests that the elevated values measured at this site are due either to impacts from Units 1 and 2 or other area sources. However, considering the over prediction in the modeling system when only the impacts from Cardinal Plant are considered and evaluation of the conditions present when elevated monitor readings and modeled values occur, it is likely that the elevated readings at this monitor are driven by emissions from Units 1 and 2 under Class A stability conditions instead of other area sources.

**Table 5. Monitor vs Modeled value statistics for 2013 data for the Storage Site Monitor Site (values in ug/m$^3$)**

| Parameter | Initial Case | Improved Cooling Tower Parameterization Case | Improved Cooling Tower Parameterization Plus 75% Core Size Case |
|---|---|---|---|
| **Monitored Peak** | 107.5 | 107.5 | 107.5 |
| **Modeled Peak** | 369.0 | 369.0 | 369.0 |
| **Percent Difference in Peaks** | -243.3 | -243.3 | -243.3 |
| **Monitored Design Value** | 86.5 | 86.5 | 86.5 |
| **Modeled Design Value** | 127.5 | 127.5 | 119.4 |
| **Percent Difference in Design Values** | -47.4 | -47.4 | -38.0 |
| **Paired Average Bias** | -0.99 | -0.99 | -0.98 |
| **Top 25 Monitored Values Average** | 67.6 | 67.6 | 67.6 |
| **Top 25 Modeled Values Average** | 125.6 | 123.5 | 119.6 |
| **Percent Difference in Top 25 Averages** | -85.8 | -82.7 | -76.9 |
| **Top 25 Values Unpaired Fractional Bias** | -0.60 | -0.58 | -0.56 |
| **Top 25 Values Average Unpaired Fractional Biases** | -0.57 | -0.56 | -0.52 |
| **Top 25 Values Standard Deviation of the Unpaired Fractional Biases** | 0.14 | 0.14 | 0.15 |

**Figure 3**. **Q-Q Plot of the three cases evaluated for the Trailer Sales Site Monitor.**




## HIGHWAY 19 MONITOR (Site ID 39-081-0018)

The Highway 19 Monitor Site was selected based on elevated modeling results directly attributable to Units 1 and 2 observed in the Unit 3 FGD Permit Modeling[9]. The Unit 1 and 2 impacts observed in the Unit 3 FGD Permit Modeling results were located somewhat differently and were of greater magnitude that the original FGD Permit Modeling results submitted as part of the permitting of the Units 1 and 2 FGD project several years earlier[12] likely due to the change from AERMOD that had been used for the Unit 1 and 2 FGD Permit Modeling to CALPUFF in the Unit 3 FGD Permit Modeling and the change from a Pittsburgh-Pittsburgh meteorology to a valley based surface meteorology collected at Follansbee, West Virginia coupled with Pittsburgh upper air data. This monitor is 4.19 kilometers from the Unit 3 Cooling Tower at a bearing of 215.2 degrees and 2.58 kilometers from the Units 1 and 2 stack at a bearing of 214.7 degrees.

In evaluating the results from this site, it's obvious that the impacts from Unit 3 are minor in nature. However, Unit 3 does not appear to influence the peak modeled readings as shown in Table 6 and Figure 4, and has only a minor impact on the design value. It is also clear from the Q-Q Plot in Figure 4 that Units 1 and 2 are the primary, but not only sources, having impacts at the site during periods of elevated readings. This is indicated by the consistent under prediction of values by the model in the range of 60 to 180 ug/m$^3$.

**Figure 4. Q-Q Plot of the three cases evaluated for the Highway 19 Monitor.**

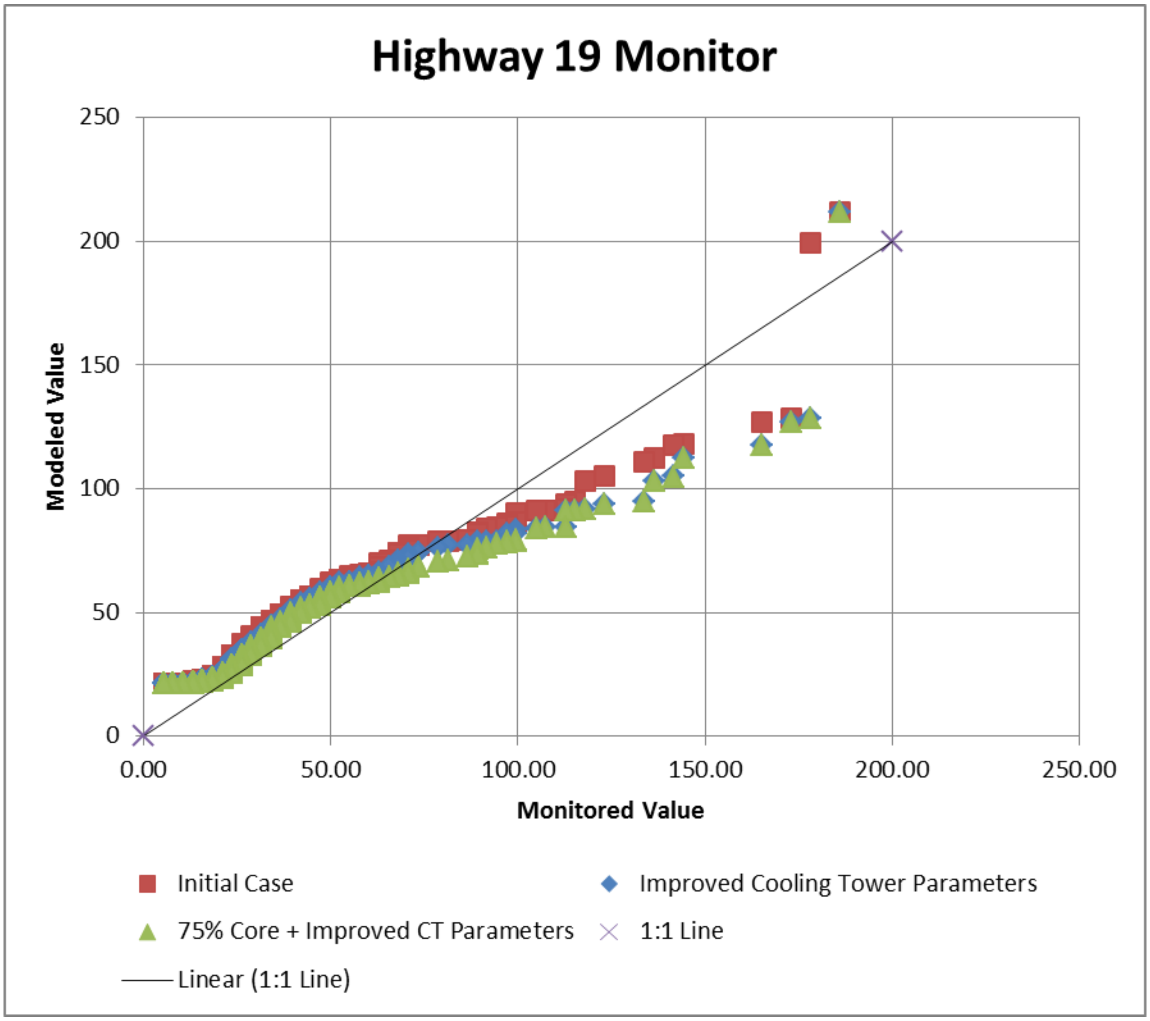


**Table 6. Monitor vs Modeled value statistics for 2013 data for the Highway 19 Monitor Site (values in ug/m$^3$)**

| Parameter | Initial Case | Improved Cooling Tower Parameterization Case | Improved Cooling Tower Parameterization Plus 75% Core Size Case |
|---|---|---|---|
| **Monitored Peak** | 186.1 | 186.1 | 186.1 |
| **Modeled Peak** | 211.6 | 211.6 | 211.6 |
| **Percent Difference in Peaks** | -13.7 | -13.7 | -13.7 |
| **Monitored Design Value** | 136.3 | 136.3 | 136.3 |
| **Modeled Design Value** | 127.1 | 117.5 | 117.5 |
| **Percent Difference in Design Values** | 6.8 | 13.8 | 13.8 |
| **Paired Average Bias** | -0.91 | -0.91 | -0.90 |
| **Top 25 Monitored Values Average** | 119.4 | 119.4 | 119.4 |
| **Top 25 Modeled Values Average** | 105.5 | 96.6 | 95.3 |
| **Percent Difference in Top 25 Averages** | 11.6 | 19.1 | 20.2 |
| **Top 25 Values Unpaired Fractional Bias** | 0.12 | 0.21 | 0.22 |
| **Top 25 Values Average Unpaired Fractional Biases** | 0.13 | 0.21 | 0.23 |
| **Top 25 Values Standard Deviation of the Unpaired Fractional Biases** | 0.09 | 0.10 | 0.09 |

## FLAT OPERATING CASE INPUTS FOR CARDINAL PLANT

Following the confirmation that the parameterization of the Unit 3 inputs provided adequate model performance from AERMOD, an effort was undertaken to develop "flat" 8760 hour inputs for all three units at Cardinal Plant for use in the SIP Modeling Study.

As described previously, the flat inputs for Units 1 and 2 were determined by selecting the 90$^{th}$ percentile values of temperature, volumetric flow, and emissions, from all hours operated on the given unit at a load greater than 580 MW. However, as has been shown in the previous cases, Unit 3 with its FGD discharge mixed into the natural draft cooling tower flow behaves in a completely different way. Due to the ambient temperature dependence of the cooling tower itself and the fact that it represents roughly 90 percent of the volumetric flow leaving the tower during operation, a static discharge case is unrealistic. Since the Unit 3 discharge characteristics are highly dependent on the ambient conditions, the following procedure was used to establish an hour by hour input to AERMOD for Unit 3 that still has some characteristics of a flat unit operation case.

Unit 3 is also slightly larger than Units 1 and 2, so to reflect this slight size difference, the load bin used for developing the FGD Discharge only portion of the calculation ($T_{fg}$ and $V_{fg}$ in Equation 2) considered all hours with a load greater than 600 MW. This resulted in a dataset containing 4807 hours. Then the 90$^{th}$ percentile values of temperature, volumetric flow, and emissions were determined from this data set. The emissions were converted into grams per second and then split with 80% of the emissions placed in the core portion of the parameterization and 20% of the emissions assigned to the total tower portion of the parameterization. The values of temperature and flow were inserted into the hourly calculation of cooling tower exit parameters as $T_{fg}$ and $V_{fg}$ and did not vary hour by hour.

The cooling tower itself was parameterized during normal operations using the same hour by information as was used in the previous cases where actual operating conditions were modeled. However, it was necessary to modify this approach somewhat during periods of start-up, shutdown, and outages where the cooling tower was not operating with a normal heat load on it or was completely out of service. For these hours, the ambient temperatures were examined and then operating periods where similar weather conditions were examined and used to develop hourly cooling tower conditions using best professional judgment of what the hour might have looked like had the unit been in normal operation. The developed temperature values were then fed into the calculations as $T_{af}$ in Equation 2. This allowed the tower to behave in a similar fashion to what would likely have existed had the unit been operating under normal load conditions.

Once all of these values were developed, the parameterization for the entire July 1, 2013 to June 30, 2014 was parameterized and an hourly input file for Unit 3 was produced in a similar fashion to one developed based on full actual operating conditions.

## REFERENCES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