DRAFT - Guam Naval Ordnance Annex Long-Term Adjustment Analysis and Wind Frequency Distribution

CSRP0027-A

CONFIDENTIAL

December 1, 2009

Prepared for:

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401

DNV Global Energy Concepts Inc.
1809 7th Avenue, Suite 900
Seattle, Washington 98101 USA
Phone: (206) 387-4200
Fax: (206) 387-4201
www.globalenergyconcepts.com
www.dnv.com

MANAGING RISK

Approvals

Prepared by Date

Reviewed by Date

Version Block

Version	Release Date	Summary of Changes
DRAFT		

Table of Contents

EXECUTIVE SUMMARY **1**

WIND RESOURCE DATA AND PROCESS OVERVIEW **1**

LONG-TERM ADJUSTMENT **1**

HUB-HEIGHT FREQUENCY DISTRIBUTIONS **4**

WIND SHEAR 4
HUB-HEIGHT WIND SPEED 5
WIND ROSE AND FREQUENCY DISTRIBUTION 5

List of Figures

Figure 1. Location of Guam Naval Ordnance Annex and Long-Term Reference Stations..... 2
Figure 2. Monthly and Diurnal Wind Shear Pattern at Site 8201 4
Figure 3. Site 8201 Annual Wind Rose at 65 m 6

List of Tables

Table 1. Investigated Long-Term Reference Station Summary 3
Table 2. Annual Average Wind Speeds..... 5
Table 3. Hub-Height Frequency Distribution by 30° Sector (65 m) 7
Table 4. Hub-Height Frequency Distribution by 30° Sector (80 m) 8

Executive Summary

DNV Global Energy Concepts Inc. (DNV-GEC) under contract with the National Renewable Energy Laboratory (NREL) conducted a long-term adjustment analysis and prepared a hub-height wind frequency distribution for the Guam Naval Ordnance Annex met tower (identified as Site 8201). Using data collected at Site 8201 from October 2008 through September 2009, DNV-GEC reviewed the site wind shear profile and developed directional frequency distributions at the two requested hub heights: 65 m and 80 m. DNV-GEC identified and obtained data from the available long-term stations in Guam; however, after analyzing the data, DNV-GEC chose not to adjust site wind speeds because doing so would not reduce the uncertainty on the long-term average wind speed.

Wind Resource Data and Process Overview

DNV-GEC collected, validated and summarized the raw data at Site 8201 on a monthly basis. A summary of the annual wind resource for October 2008 through September 2009 can be found in the *Guam Naval Ordnance Annex Data Summary and Retrieval for September 2009*. The corresponding validated data set was utilized for this analysis. DNV-GEC consulted nearby long-term reference stations to determine how well the on-site data represent the long-term average wind speeds and whether a long-term adjustment would be appropriate. Wind speeds measured by anemometers at different heights were used to calculate the wind shear. Then, the shear calculations were used to extrapolate wind speeds at the measurement heights to the turbine hub-heights, 65 m and 80 m.

Long-Term Adjustment

Regional long-term meteorological (met) data used in this analysis were collected from the AB Won Pay International Airport – both the Agana Automated Surface Observing System (Agana ASOS) and a radiosonde observation station (Agana RAOB), Andersen Air Force Base (Andersen ASOS), Guam Power Authority (GPA) met tower at the Cabras-Piti power plant, and modeled data from the U.S. National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis Project (Reanalysis) grid point at N 12.5^{o}, E 145°. The location of the sites in relation to the Guam Naval Ordnance Annex is shown in Figure 1.

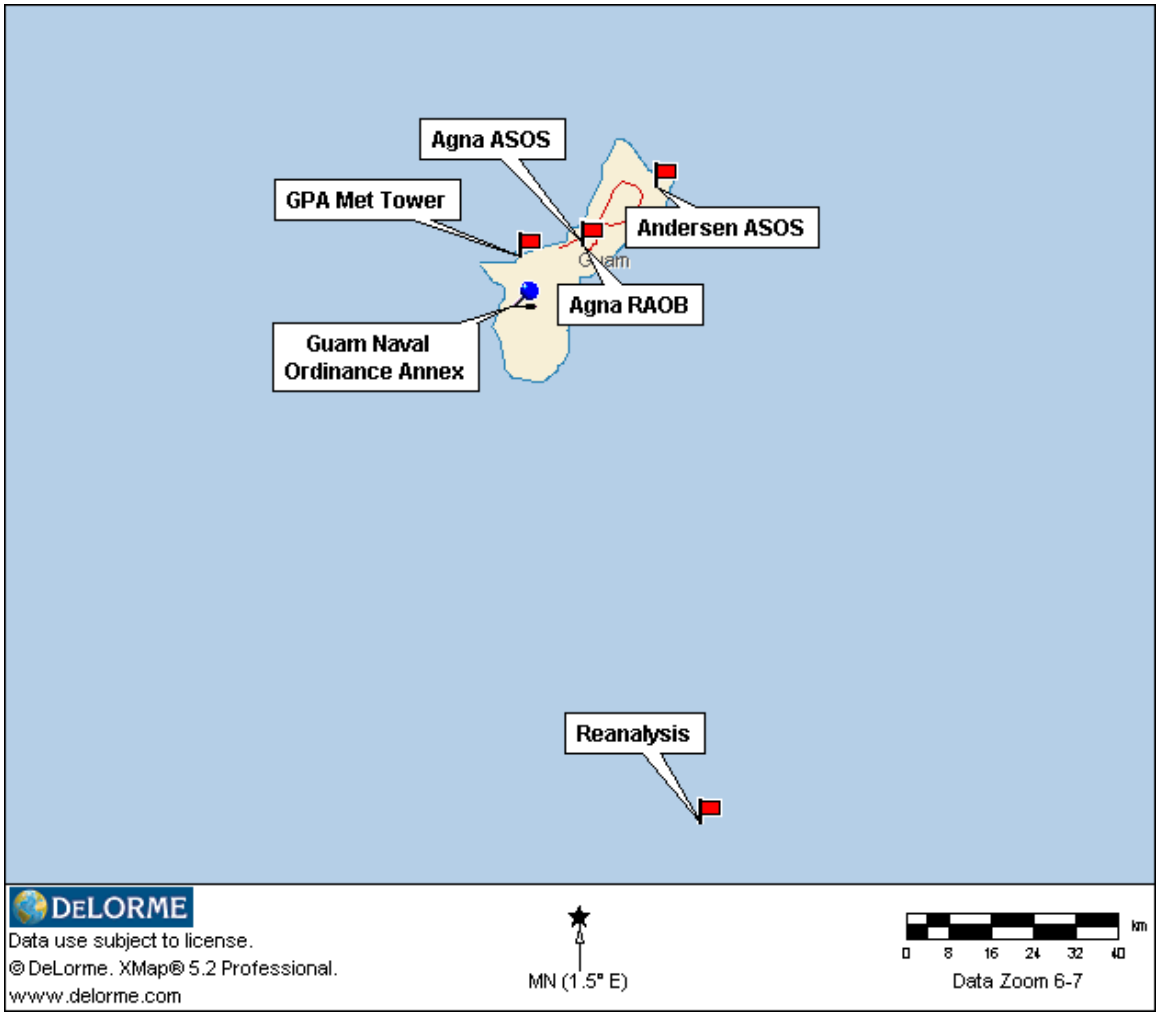

Figure 1. Location of Guam Naval Ordnance Annex and Long-Term Reference Stations

Details of the correlation between average monthly wind speeds at Site 8201 and each long-term station considered are shown in Table 1. The table also presents other considerations for determining the suitability of the long-term reference stations. With the exception of the GPA met tower (due to poor data recovery), all stations in Table 1 were used qualitatively to determine the viability of a long-term adjustment at Site 8201.

Table 1. Investigated Long-Term Reference Station Summary

Reference Station	Sensor Height (m)	R-Squared Correlation to On-Site Data (Monthly)	Period of Record	Distance from Site (km)	Sensor Change	Notes
Agana ASOS	10	0.96	1996-2009	30	08/2004	Period since sensor change was used in calculations; Daily R^2 = 0.87
Agana RAOB	1000	0.87	2000-2009	30	N/A	
Andersen ASOS	10	0.97	2005-2009	47	No	Daily R^2 = 0.88
Reanalysis (12.5ºN, 145ºE)	Approx 750 (925 mb)	0.69	1981-2009	99	N/A	
GPA Met Tower	60	N/A	2005-2009	10	N/A	Extremely low recovery for same period of record as Site 8201 (~44%)

The correlation between the monthly and daily average wind speeds at the Agana ASOS and Andersen ASOS stations were relatively high. However, there is significant uncertainty associated with using these stations to make a long term adjustment because the Agana ASOS station predicted an upward long-term adjustment of 3.5% while the Andersen ASOS predicted a downward long-term adjustment of 2.7%.

The Agana RAOB station and Reanalysis model had lower correlation values as well as inherently higher uncertainty. The uncertainty is high when using the RAOB data because balloons are launched twice daily, and upper-atmosphere measurements are compared with the on-site surface measurements. The uncertainty is high using the Reanalysis model partly due to coarse resolution; the model output is averaged over a 2.5º by 2.5º latitude/longitude grid. Therefore, including the RAOB station and Reanalysis model data would not have reduced the uncertainty in adjusting the measured on-site wind speeds to the long-term average.

Additionally, the recovery level at the GPA met tower was extremely low during the same period of record at Site 8201, thus discounting it immediately from the analysis process. Consequently, after analyzing data from all of the available long-term stations, DNV-GEC chose not to adjust site wind speeds, and instead to use the one year of on-site measurements as representative of the long-term average wind speeds. Continued data collection at Site 8201 is recommended to establish a long-term reference for wind development on Guam.

Hub-Height Frequency Distributions

Wind Shear

Vertical wind shear (shear) is the change of wind speed with height above ground level. Hub-height wind speeds at the met tower location were estimated by applying the monthly diurnal wind shear pattern measured at the Site to the 58-m wind data. DNV-GEC calculated the wind shear exponent[1] between the 40-m and 58-m anemometers for sensors located on booms that share the same orientation. Only wind speeds greater than 4 m/s were included in the calculation. We calculated shear using the northeast-oriented anemometers, except during instances when these anemometers were considered invalid, in which case shear was calculated between the southeast-oriented anemometers. To mitigate potential directional differences, DNV-GEC compared the calculated shear between the 58-m northeast and 40-m northeast anemometers and the 58-m southeast and 40-m southeast anemometers and found the marginal differences. The annual shear at Site 8201 was calculated to be approximately 0.18. Shear was applied to upper-level wind speeds on a monthly and diurnal basis to estimate hub-height wind speeds. The monthly and diurnal wind shear pattern is shown in Figure 2.

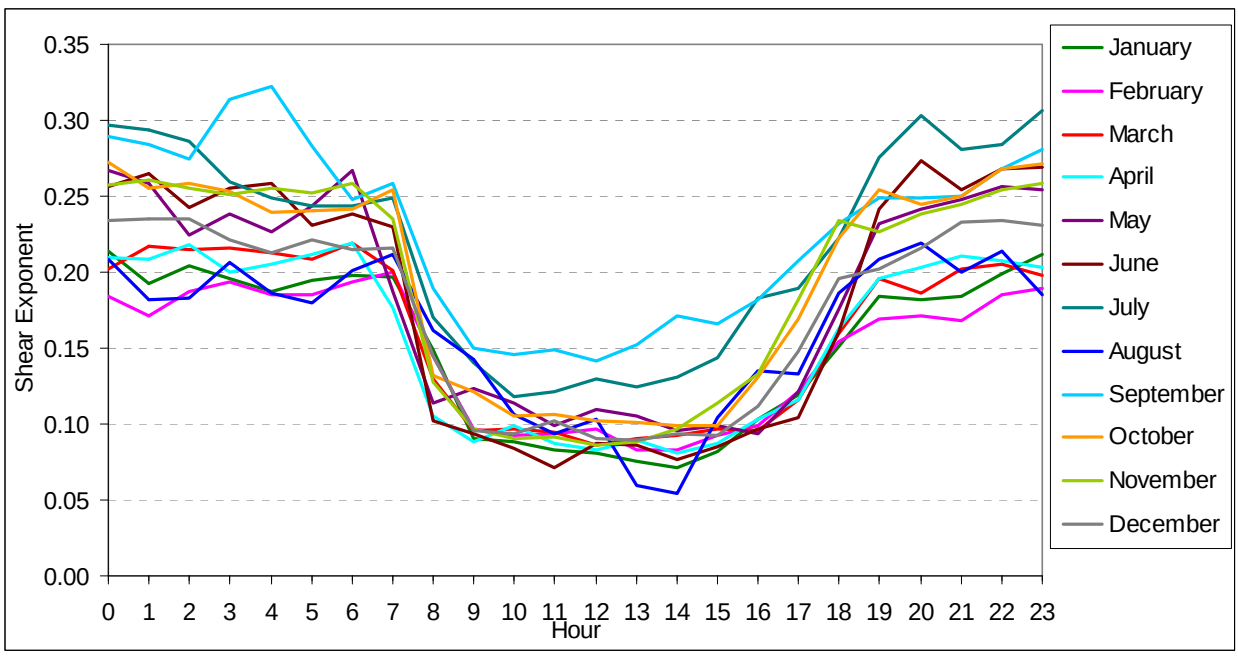

Figure 2. Monthly and Diurnal Wind Shear Pattern at Site 8201

[1] Wind shear describes the typical increase in wind speed at greater heights above the ground. The wind shear exponent (alpha or α) is one method of describing the extent to which wind speeds vary with increasing height above ground level. The equation that uses the exponent is $(V_1 / V_2) = (H_1 / H_2)^{\alpha}$, where V_1 and V_2 are wind speeds at heights H_1 and H_2, respectively (measured from the ground level), and α is the dimensionless wind shear exponent.

Hub-Height Wind Speed

Based on the measured 58-m wind speeds and the diurnal monthly wind shear pattern at the Site 8201, DNV-GEC developed wind speed frequency distributions representing the hub-height (65 m and 80 m) wind speeds and wind directions at the met tower location. To generate frequency distributions, DNV-GEC binned data from each tower over its entire period of record by wind speed and direction. To normalize the data set to 8,760 hours, DNV-GEC developed a monthly record-length correction factor by counting the number of records with valid upper-level sensor wind speed and wind direction observations available in each month. The data were then categorized by wind direction sector (30° sectors centered on 0°, 30°, etc.) and wind speed bin (intervals of 0.5 m/s centered on 0.5 m/s, 1.0 m/s, etc.) to generate the hub-height annual frequency distribution showing the number of observations in each wind speed bin and for each wind direction sector. The annual hub-height (65 m and 80 m) wind speeds computed from the frequency distributions are presented in Table 2. As discussed in the previous section, DNV-GEC did not make a long-term adjustment to these wind speeds.

Table 2. Annual Average Wind Speeds

Met Tower	58-m Measured Wind Speed (m/s)	65-m Estimated Wind Speed (m/s)	80-m Estimated Wind Speed (m/s)
8201	8.0	8.1	8.4

Wind Rose and Frequency Distribution

A wind rose depicts the frequency and energy content of wind by direction. The annualized wind rose estimated at 65 m for Site 8201 is presented in Figure 3. The wind rose at 80 m was similar; therefore, only the 65-m wind rose is shown below. As shown in the Figure 3, significant energy-producing winds come from the east and east-southeast.

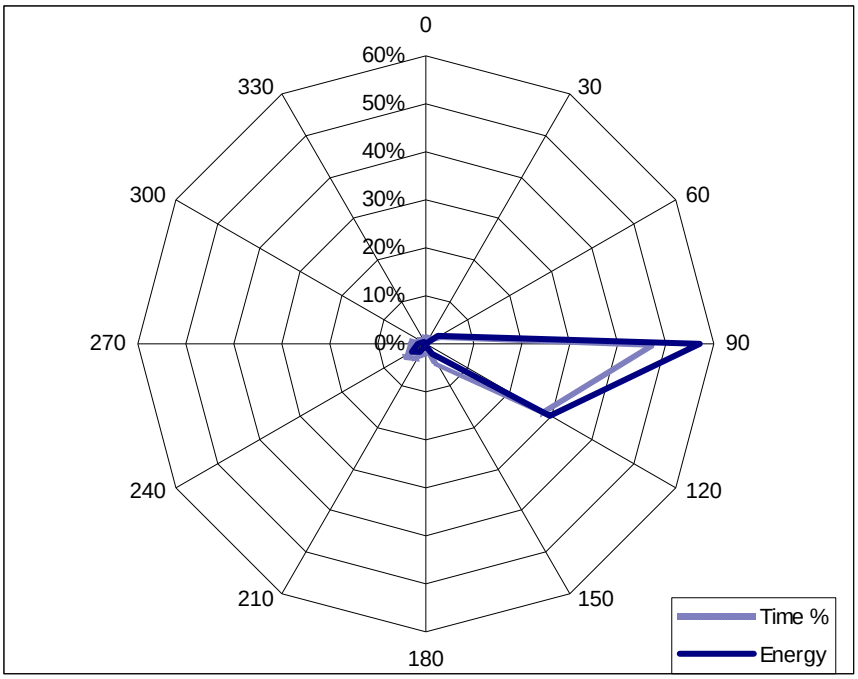

Figure 3. Site 8201 Annual Wind Rose at 65 m

The 65-m directional frequency distribution can be found in Table 3 and the 80-m directional frequency distribution can be found in Table 4.

Table 3. Hub-Height Frequency Distribution by 30° Sector (65 m)

Wind Speed Bins	0	30	60	90	120	150	180	210	240	270	300	330	Weighted Hours
0.5	2.2	0.7	2.2	4.4	5.5	5.0	0.5	1.2	5.3	9.2	3.7	2.2	42.1
1.0	2.2	1.1	1.6	2.9	5.2	1.4	3.6	2.8	4.2	4.5	2.3	2.0	33.8
1.5	3.0	1.7	3.8	5.8	4.5	3.2	3.8	2.6	4.5	7.1	3.4	3.4	46.6
2.0	4.9	4.7	5.7	6.4	8.7	6.5	5.4	5.5	6.1	7.4	5.7	8.1	75.2
2.5	8.0	7.5	5.5	12.2	13.5	9.5	7.2	7.2	8.1	10.5	6.6	6.2	101.8
3.0	4.4	6.4	8.3	19.6	22.0	12.8	9.9	9.8	15.7	14.6	11.1	4.3	138.7
3.5	6.0	5.5	11.4	26.4	32.3	16.5	11.2	13.2	20.4	17.9	15.0	5.2	181.0
4.0	4.9	4.6	11.0	32.7	38.4	19.3	12.4	14.7	31.4	18.5	13.8	4.9	206.5
4.5	2.9	2.4	11.1	46.5	65.0	25.9	14.8	21.7	18.7	18.6	9.8	4.9	242.2
5.0	1.5	3.6	12.5	69.9	86.1	30.3	15.4	24.6	18.8	17.2	11.3	4.2	295.4
5.5	2.5	2.8	16.0	98.1	117.7	37.9	17.4	29.9	19.5	16.3	9.6	5.7	373.4
6.0	2.4	4.1	18.3	137.0	147.4	36.4	16.6	28.9	26.2	15.9	8.8	2.7	444.6
6.5	2.4	4.5	12.3	193.7	171.9	29.3	10.9	27.6	28.3	12.7	3.7	1.5	498.7
7.0	1.3	1.8	16.0	259.3	219.6	28.1	9.0	21.5	29.6	7.9	5.7	2.4	602.1
7.5	1.5	1.8	17.8	294.5	218.9	22.1	5.7	18.1	24.2	7.8	5.7	2.5	620.4
8.0	0.2	1.2	26.4	337.5	220.2	20.6	1.5	12.7	25.2	7.4	4.0	2.6	659.4
8.5	0.0	0.7	24.2	335.5	212.0	10.7	1.4	10.6	22.6	7.9	3.4	1.2	630.1
9.0	0.0	0.8	25.3	331.1	198.1	9.7	0.9	10.0	17.8	4.7	1.8	1.0	601.2
9.5	0.2	0.0	18.7	326.6	169.4	10.3	0.9	7.6	12.0	3.8	1.9	0.8	552.1
10.0	0.0	0.0	12.2	312.1	147.3	7.3	0.4	5.3	11.6	5.0	1.0	0.5	502.6
10.5	0.0	0.0	8.7	290.2	114.6	5.4	0.8	3.8	8.1	4.4	1.6	0.2	437.9
11.0	0.0	0.0	4.1	228.3	89.8	3.3	0.3	4.1	6.6	2.9	1.1	0.2	340.6
11.5	0.0	0.0	3.1	195.8	58.8	3.8	0.0	1.4	8.0	4.8	0.3	0.0	276.0
12.0	0.2	0.0	1.7	151.5	38.3	3.2	0.1	2.1	5.0	5.7	1.0	0.0	208.7
12.5	0.0	0.0	0.5	113.6	31.3	2.6	0.2	2.1	6.2	5.5	0.7	0.0	162.7
13.0	0.0	0.0	0.5	86.0	18.3	2.0	0.0	1.6	5.2	7.3	0.5	0.0	121.4
13.5	0.0	0.0	0.9	58.6	16.0	1.1	0.0	2.7	7.2	6.2	0.1	0.0	92.7
14.0	0.0	0.0	0.0	48.5	12.8	0.8	0.0	2.2	6.7	4.4	1.0	0.0	76.3
14.5	0.0	0.0	0.5	40.5	11.2	0.3	0.0	0.7	4.5	4.1	0.2	0.0	62.1
15.0	0.0	0.0	0.0	24.7	8.2	0.7	0.0	0.2	2.1	2.3	0.1	0.0	38.3
15.5	0.0	0.0	0.7	19.5	6.9	0.3	0.0	0.4	3.6	1.1	0.2	0.0	32.7
16.0	0.0	0.0	0.0	14.3	5.0	0.2	0.0	0.1	2.0	0.7	0.0	0.0	22.2
16.5	0.0	0.0	0.0	7.3	2.7	0.3	0.0	0.0	1.4	0.5	0.0	0.0	12.2
17.0	0.0	0.0	0.0	3.7	3.3	0.2	0.0	0.0	0.9	0.1	0.0	0.0	8.2
17.5	0.0	0.0	0.0	3.7	2.3	0.0	0.0	0.0	0.7	0.5	0.0	0.0	7.3
18.0	0.0	0.0	0.0	1.5	1.5	0.0	0.0	0.0	0.2	0.2	0.0	0.0	3.4
18.5	0.0	0.0	0.0	1.4	2.2	0.0	0.0	0.0	0.0	0.2	0.0	0.0	3.7
19.0	0.0	0.0	0.0	0.3	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3
19.5	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	0.2	0.0	0.0	1.7
20.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.2	0.2	0.0	0.0	1.8
Total	**50.6**	**55.8**	**280.7**	**4141.6**	**2531.8**	**367.0**	**149.9**	**296.9**	**418.3**	**265.7**	**135.0**	**66.7**	**8760.0**

Table 4. Hub-Height Frequency Distribution by 30° Sector (80 m)

Wind Speed Bins	0	30	60	90	120	150	180	210	240	270	300	330	Weighted Hours
0.5	2.0	0.7	1.9	4.4	5.5	4.9	0.5	1.2	5.1	8.6	3.5	2.2	40.4
1.0	1.9	1.0	1.8	2.9	5.0	1.6	2.9	2.7	4.2	4.4	2.1	1.8	32.2
1.5	3.1	1.5	3.3	4.4	3.3	3.1	4.2	2.5	4.1	6.8	3.4	3.1	42.7
2.0	3.7	4.0	5.1	6.5	8.1	5.2	5.2	4.9	5.9	7.5	5.7	7.8	69.5
2.5	7.7	6.8	5.5	10.5	12.8	8.9	6.2	6.4	7.6	8.5	5.5	6.3	92.7
3.0	6.0	6.3	7.5	16.6	16.6	11.8	9.2	8.8	12.4	14.6	10.9	3.4	124.1
3.5	4.5	5.7	10.1	23.9	29.8	14.9	10.8	13.1	17.9	16.3	13.0	6.3	166.5
4.0	4.5	4.8	10.4	31.5	36.0	18.6	11.5	13.5	28.5	18.2	14.0	3.9	195.3
4.5	3.7	2.6	9.6	34.6	50.2	20.5	11.6	16.2	23.4	16.9	9.8	4.6	203.6
5.0	2.2	3.2	12.3	60.7	75.7	27.5	15.1	22.6	16.9	18.6	9.9	4.2	268.8
5.5	2.1	3.6	14.1	82.4	94.4	32.6	17.3	25.0	19.8	14.6	9.5	4.9	320.3
6.0	3.1	2.9	17.5	106.9	137.9	36.1	15.7	31.9	21.9	16.9	9.9	3.9	404.5
6.5	1.8	4.8	14.6	155.2	143.4	32.2	12.6	28.7	24.6	12.2	5.6	1.9	437.4
7.0	1.2	2.4	10.3	213.8	193.0	24.5	9.5	23.5	29.5	9.8	5.5	1.8	525.0
7.5	1.1	2.2	20.3	270.0	209.8	27.4	8.5	19.2	25.9	8.2	4.5	2.3	599.3
8.0	1.4	1.5	18.6	313.8	218.4	22.7	3.8	14.8	25.0	8.1	5.9	2.9	636.9
8.5	0.2	0.8	24.1	332.6	207.6	16.5	1.0	12.2	22.4	6.1	2.5	2.0	627.9
9.0	0.0	0.8	23.3	324.7	197.7	11.2	1.1	8.1	20.0	6.9	3.4	1.4	598.5
9.5	0.2	0.2	23.1	324.8	192.0	10.1	0.7	9.4	14.3	3.7	1.3	0.7	580.3
10.0	0.0	0.0	17.8	320.3	165.7	7.1	0.9	6.8	11.0	5.1	1.6	1.0	537.3
10.5	0.0	0.0	10.0	302.9	135.1	7.3	0.3	4.8	9.9	3.3	1.3	0.2	475.0
11.0	0.0	0.0	7.6	270.5	107.4	4.8	0.9	3.4	7.6	4.2	1.7	0.0	408.1
11.5	0.0	0.0	5.0	223.4	79.7	3.7	0.3	2.9	7.6	3.6	0.6	0.2	326.8
12.0	0.0	0.0	2.7	172.5	52.7	2.2	0.0	2.1	7.5	5.0	0.6	0.0	245.2
12.5	0.2	0.0	1.6	137.8	36.6	3.3	0.1	1.7	4.2	4.6	0.6	0.0	190.6
13.0	0.0	0.0	0.7	106.5	26.0	2.8	0.2	1.7	5.9	5.5	0.7	0.0	150.0
13.5	0.0	0.0	0.2	78.2	18.2	2.0	0.0	1.7	6.2	7.0	0.4	0.0	113.8
14.0	0.0	0.0	0.9	57.3	15.0	1.3	0.0	2.3	5.3	5.8	0.2	0.0	88.1
14.5	0.0	0.0	0.2	46.8	10.5	0.8	0.0	2.1	6.0	4.3	0.5	0.0	71.1
15.0	0.0	0.0	0.3	35.6	11.7	0.1	0.0	1.4	5.1	3.9	0.8	0.0	59.0
15.5	0.0	0.0	0.3	22.9	8.0	0.7	0.0	0.4	3.4	3.2	0.1	0.0	38.9
16.0	0.0	0.0	0.3	17.8	6.0	0.3	0.0	0.2	1.8	0.8	0.0	0.0	27.4
16.5	0.0	0.0	0.0	13.3	5.5	0.0	0.0	0.4	2.7	1.1	0.2	0.0	23.2
17.0	0.0	0.0	0.0	7.2	2.2	0.5	0.0	0.0	1.3	0.5	0.0	0.0	11.6
17.5	0.0	0.0	0.0	3.2	3.2	0.2	0.0	0.0	1.6	0.2	0.0	0.0	8.3
18.0	0.0	0.0	0.0	3.0	2.3	0.0	0.0	0.0	1.0	0.4	0.0	0.0	6.8
18.5	0.0	0.0	0.0	1.2	1.8	0.0	0.0	0.0	0.5	0.3	0.0	0.0	3.9
19.0	0.0	0.0	0.0	0.8	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3
19.5	0.0	0.0	0.0	0.7	1.8	0.0	0.0	0.0	0.0	0.2	0.0	0.0	2.7
20.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	1.5
20.5	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.2	0.0	0.0	1.5
21.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Total	**50.6**	**55.8**	**280.7**	**4141.6**	**2531.8**	**367.0**	**149.9**	**296.9**	**418.3**	**265.7**	**135.0**	**66.7**	**8760.0**