AECOM

Environment

Submitted to:
Dominion
Warren County Combined-Cycle Project

Submitted by:
AECOM North Carolina, Inc.
Raleigh, NC
601369071400
Revision 1 – February 2010

Air Quality Dispersion Modeling Protocol

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1.0 Introduction

1.1 Project Overview

Virginia Electric and Power Company (Dominion) is currently permitted (Air Permit No. 81391) to construct and operate a power generating facility, herein referred to as the "Warren County Project", on a 38.6-acre parcel located in Warren and Kelley Industrial Parks, approximately one mile north of Interstate Route 66 in Warren County, Virginia. The present permitted combustion turbine generator (CTG) facility consists of three possible scenarios for the final configuration of the facility:

- Two one-on-one GE 7FA CTGs
- two-on-one GE 207FA CTGs
- two-on-one Siemens SGT6-5000F CTGs

However, in response to the projected market demand for electrical power, Dominion is applying for a revised Prevention of Significant Deterioration (PSD) permit from the Virginia Department of Environmental Quality (VA DEQ) that will allow for one of three potential plant configurations. The key elements of the proposed project will be one of the following turbine configurations:

- Option 1 – 3x3x1 Siemens SGT6-5000F units,

OR

- Option 2 – 3x3x1 Mitsubishi M501GAC units.

OR

- Option 3 – 3x3x1 General Electric (GE) 7FA05 units.

The same auxiliary equipment is being proposed for each of the three turbine configurations and the details of which are presented in Section 2. A copy of the USGS topographic map showing the site location is presented in Section 2 of this document.

1.2 Purpose of Modeling Protocol

The purpose of this document is to present the proposed methodology for Class I and Class II area air dispersion modeling analyses that will be performed in support of the air permit application for the Warren County Project. Modeling methods and assumptions, including model selection and options, meteorological data and source parameters to be used in the modeling analyses, are presented in this document for review by VA DEQ.

1.3 Contents of the Modeling Protocol

This protocol document consists of seven sections. Section 1 provides an introductory presentation. Section 2 contains a project description, including information regarding the plant's location and the expected air pollutant emissions. Sections 3 - 5 present a detailed description of the modeling approach proposed to be used in evaluating air quality impacts of the proposed project including model selection criteria, good engineering practice stack height determination, refined modeling analyses, ambient air quality compliance, and additional impacts analyses. Section 6 presents the description of the result analysis that will be submitted to VA DEQ. Section 7 documents the references that were used in preparing this document. Appendix A contains the preliminary site plans of the plant for all the three turbine configurations. Appendices B and C contain papers supporting the execution of the PLUVUE model.

2.0 Project Description

This section describes several aspects of the proposed project that are relevant for the proposed air quality modeling analysis.

2.1 New Generating Station Location and Layout

The proposed plant will be constructed on a 38.6-acre site located in the Warren and Kelly Industrial Parks, approximately one mile north of Interstate Route 66. This is the same location as the previously permitted project. A topographical map of the site region is shown in Figure 2-1. A preliminary site plan for all the three turbine configurations, showing the plant property and adjacent roadways, is presented in Appendix A.

2.2 Process Description

The following section provides an overview of the plant to be described in greater detail in the permit application. The proposed plant is a combined-cycle power plant to be located in Warren County, Virginia. Dominion is applying for an air quality permit that will allow for one of three potential plant configurations. The key emission source for the proposed project will be one of the following:

- Option 1 – 3x3x1 Siemens SGT6-5000F units,

OR

- Option 2 – 3x3x1 Mitsubishi M501GAC units.

OR

- Option 3 – 3x3x1 GE 7FA05 units.

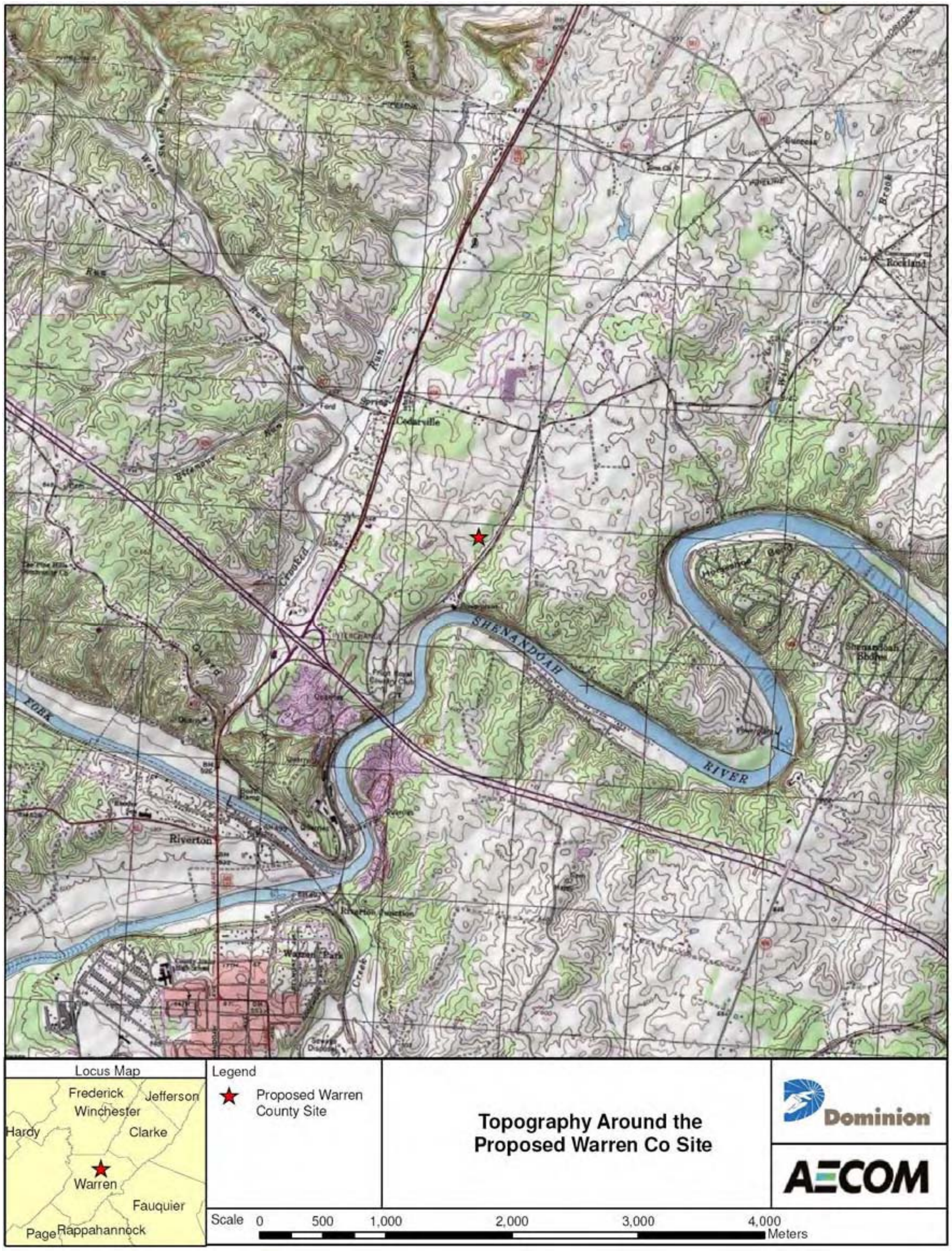
The plant will be fueled by pipeline-quality natural gas only; there is no provision for backup operation on fuel oil. The same auxiliary equipment is being proposed for either of the three turbine configurations and is listed below:

- Three supplementary fired, Heat Recovery Steam Generators (HRSGs)
- One reheat condensing steam turbine generator (STG)
- Three Inlet turbine chiller – one for each of the turbines
- One Auxiliary Boiler
- One Diesel-Fired Emergency Generator

- One Diesel- Fired Fire Water Pump, and
- One Fuel Gas Heater.

Based on preliminary emissions calculations, the proposed plant (either of the three turbine configurations) will be subject to PSD review for Carbon Monoxide (CO), Nitrogen dioxide (NO_2), particulate matter less than ten microns (10 μm) in diameter (PM_{10}), Particulate matter less than 2.5 microns in diameter ($PM_{2.5}$), Sulfuric Acid (H_2SO_4) and Volatile Organic Compounds (VOC). The plant is not expected to be a major source of hazardous air pollutants.

Figure 2-1 Location of Proposed Warren County Combined-Cycle Project



2.2.1 Combined-cycle Technology

The proposed project will use combined-cycle power generation technology to maximize generation efficiency and minimize fuel use. Combined-cycle technology is nearly 60 percent more efficient and has the ability to generate power faster than vintage steam-electric central utility power plants. Since combined-cycle units burn less fossil fuel to generate an equivalent amount of power, they also emit substantially less air pollutants, including CO_2 (a greenhouse gas), and will play an important role in meeting potential national CO_2 emissions targets in the future.

The production of electricity using a combustion turbine engine coupled with a shaft-driven generator is referred to as the Brayton Cycle, or “simple-cycle”. The Rankine Cycle represents the traditional methods of generating power from utility steam electric power plants. In this cycle, boilers are used to produce high-pressured steam, which is expanded in a steam turbine to drive an electric generator. This Rankine cycle has a typical thermal efficiency of less than 35 percent. The largest energy losses from this cycle are from the boiler stack, which exhausts at about 350°F and from heat injected in the steam turbine condenser. Due to their low thermal efficiency, these plants were traditionally designed to burn low grade fuels such as coal or residual fuel oil. Relatively high stack temperatures are necessary with these fuels in order to prevent stack corrosion. The need to eject large quantities of heat from the steam turbine is the reason many utility power plants were sited next to a large source of cooling water.

The proposed project will combine the Brayton and Rankine cycles (hence, “combined-cycle”) to maximize thermal efficiency. Natural gas will be burned in three Brayton Cycle turbines which will generate half of the electrical output. Instead of being discarded to the environment, the exhaust heat will be recovered in a Rankine Cycle HRSG/steam turbine, and the heat will be extracted until the exhaust temperature is about 200°F before being discharged through the stacks. This will result in an overall thermal efficiency of about 55 percent. In other words, the combined-cycle turbines will consume only two thirds of the fuel that would be consumed in a conventional utility power plant to produce the same amount of electricity. This state-of-the-art, high efficiency technology combined with the use of the cleanest fossil fuel (natural gas), will yield annual emissions that are a small fraction of those of a conventional power plant.

2.2.2 Major Facility Components

The primary sources of pollutants associated with the proposed project are the three natural gas-fired CTGs. Other potential sources of criteria pollutants associated with the proposed project include three six-cell inlet turbine chillers (one for each turbine), an auxiliary boiler, a fuel gas heater, a diesel-fired emergency generator, and a diesel-fired fire water pump. A brief description of the major components of the proposed project is provided in the following sections. For this project, AECOM proposes to conduct an air dispersion modeling analysis for the CTGs, inlet turbine chillers, auxiliary boiler, diesel-fired emergency generator, diesel-fired fire water pump, and fuel gas heater.

2.2.2.1 Gas Turbines

The proposed project includes the installation of three natural gas-fired turbines in combined-cycle mode, each provided with its own duct-fired HRSG and a common steam turbine generator. Dominion is applying for an air quality permit that will allow three optional plant configurations: Siemens SGT6-5000F **OR** Mitsubishi M501GAC **OR** GE 7FA05.

The combined-cycle turbines will be fired by pipeline natural gas. No restriction on the annual operation of each combined-cycle combustion turbine is expected (8,760 hours/year). Each gas turbine power block will include an advanced firing temperature combustion turbine air compressor section, gas combustion system (utilizing dry, low NO_x combustors), power turbine, and a generator.

The gas turbine is the main component of a combined-cycle power system. First, air is filtered, cooled and compressed in a multiple-stage axial flow compressor. Compressed air and fuel are mixed and combusted in the turbine combustion chamber. Lean pre-mix dry low-NO_x combustors minimize NO_x formation during natural gas combustion. Hot exhaust gases from the combustion chamber are expanded through a multi-stage power turbine that results in energy to drive both the air compressor and electric power generator.

The exhaust gas exiting the power turbine in the combined-cycle turbines is ducted to an unfired boiler commonly known as a Heat Recovery Steam Generator, where steam is produced to generate additional electricity in a steam turbine-generator. Natural gas-fired duct burners located within the HRSGs are used for supplementary firing to increase steam output.

The combustion turbines are designed to operate in the dry low-NO_x mode at loads from about 60 percent up to 100 percent load rating for the proposed Siemens SGT6-5000F and Mitsubishi M501GAC and from low load up to 100 percent load rating for the proposed GE 7FA05 combustion turbines. “Low load” for the GE turbines is 50% at 0º and 59ºF and 55% at 100ºF. The proposed combustion turbines will normally be taken out of service for scheduled maintenance, or as dictated by economic or electrical demand conditions.

2.2.2.2 Heat Recovery Steam Generators (HRSG)

A horizontal, natural circulation, three-pressure level HRSG system will extract heat from the exhaust of each proposed combined-cycle gas turbine. Exhaust gas entering the HRSG at approximately 1,100°F will be cooled to 200°F by the time it leaves the HRSG exhaust stack. Steam production in the HRSGs will be augmented using duct burners that will be fired by natural gas. The heat recovered is used in the combined-cycle plant for additional steam generation and natural gas/feedwater heating. Each HRSG will include a high-pressure superheater, high-pressure evaporator, high-pressure economizer, reheat section (to reheat partially expanded steam), intermediate-pressure superheater, intermediate-pressure evaporator, intermediate-pressure economizer, low-pressure superheater, low-pressure evaporator, and surface condensate/feedwater preheater. The surface condenser will use the air-cooled condenser to condense the steam exhausting from the STG. As the steam is condensed, the condensate flows to the surface condenser hotwell. Control devices such as Selective Catalytic Reduction (SCR) and Oxidation Catalysts will be installed to control NO_x and CO respectively.

2.2.2.3 Steam Turbine

The proposed project includes one reheat, condensing steam turbine designed for variable pressure operation. The high-pressure portion of the steam turbine receives high-pressure super-heated steam from the HRSGs, and exhausts to the reheat section for the HRSGs. The steam from the reheat section for the HRSGs is supplied to the intermediate-pressure section of the turbine, which expands to the low-pressure section. The low-pressure turbine also receives excess low-pressure superheated steam from the HRSGs and exhausts to the surface condenser. The steam turbine set is designed to produce up to additional 539 MW of electrical output (including duct firing operations).

2.2.2.4 Inlet Turbine Chillers

Small cooling towers will be incorporated to provide cooling to the chillers used in the inlet cooling system for each turbine. Each of the three inlet turbine chillers (one each for the proposed natural gas-fired combustion turbine) is equipped with a 6-cell cooling tower.

2.2.2.5 Auxiliary Boiler

Dominion proposes to add an 88.1 MMBtu/hr auxiliary boiler to supply steam seal to the STG at start-up and at cold starts to warm up the STG rotor. The auxiliary boiler will combust natural gas only. The steam from the auxiliary boiler will not be used to augment the power generation of the CTGs or the STG. Dominion requests the boiler to be permitted to operate without annual operating restrictions, and the air quality modeling analysis reflects this assumption.

2.2.2.6 Diesel-Fired Emergency Generator

One (1) diesel-fired emergency generator will be located on-site and operated up to 500 hours per year. The emergency diesel generator will provide power in emergency situations for turning gears, lube oil pumps, auxiliary cooling water pumps and water supply pumps. The emergency diesel generator is not intended to provide sufficient power for a black start.

2.2.2.7 Diesel-Fired Fire-Water Pump Engine

One (1) diesel engine will be located on-site and operated as fire-water pump driver. The plant operations' plan calls for the unit to be operated up to 500 hours per year.

2.2.2.8 Fuel Gas Heater

Dominion proposes to add a 52.0 MMBtu/hr fuel gas heater. The heater will be used as a means to warm up the incoming natural gas fuel to prevent freezing of the gas regulating valves under certain gas system operating conditions. The heater will fire natural gas exclusively. Dominion requests the heater to be permitted to potentially operate 8,760 hours per year.

2.2.2.9 Fuel Gas System

Pipeline quality natural gas will be delivered to the plant boundary at a pressure sufficient for use in the CTGs without additional fuel compression.

The gas will first be sent through a knockout drum for removal of any liquid which may have been carried through from the pipeline. The gas then passes through a filter/separator to remove particulate matter and entrained liquid. The gas flows through the filter/separator's first chamber, the filtration section, which removes particulate matter. The gas then flows through the coalescing filters, where entrained liquid is coalesced on the filter cartridges, drops to the bottom of the chamber and either vaporizes and returns to the main gas stream or drains to the sump below. The gas then passes to the second chamber, the separation section, where any entrained liquid remaining in the stream is further separated by impingement on a net or labyrinth and drains to the bottom sump. Three filter/separators are included; one for each CTG. Hydrocarbon liquids in the sump are removed for off-site disposal. The gas is split into three streams, one for each CTG. Finally, the gas is delivered to the CTGs and burned as part of the power generation operation. Similarly the gas will also be delivered to the auxiliary boiler and the three duct burners.

2.3 Pollutant Emissions

2.3.1 Criteria Pollutant Emissions

Pollutant emissions to the atmosphere from the proposed plant will occur primarily from combustion of fuel in the combustion turbines and to a much lesser extent, from operation of the inlet turbine chillers, auxiliary boiler, emergency diesel generator, fire-water pump, and fuel gas heater. Pollutant emissions information presented in the document is preliminary and is subject to change prior to submittal of the construction permit application.

As mentioned previously, Dominion will be applying for an air quality permit that will allow either of the three turbine configurations: Siemens SGT6-5000F **OR** Mitsubishi M501GAC **OR** GE 7FA05. However, the same auxiliary equipment is proposed irrespective of the turbine configuration. Table 2-1 lists the maximum hourly emission rates of criteria pollutants from the inlet turbine chillers, auxiliary boiler, emergency generator, fire-water pump, and fuel gas heater.

Potential annual emissions of criteria pollutants from the Warren County Project are presented in Tables 2-4, 2-6 and 2-8 for each of the three turbine configurations respectively. The potential annual emissions are based on the following:

- The annual emission rate for the combined-cycle turbines is based on 8,760 hours per year.
- The inlet turbine chiller will operate up to 8,760 hours per year.
- The auxiliary boiler will operate up to 8,760 hours per year.
- The diesel fired fire-water pump and diesel emergency generator will be operated no more than 500 hours per year each.
- The fuel gas heater will operate up to 8,760 hours per year.

Table 2-1 Preliminary Maximum Hourly Emission Rates of Criteria Pollutants from the Auxiliary Equipment

Pollutant	Maximum Hourly Emission Rates (lb/hr)[1]					
	NO_X	CO	PM_{10}	$PM_{2.5}$	SO_2	VOC
Inlet Turbine Chiller [2]	--	--	5.99E-03	1.84E-05	--	--
Auxiliary Boiler	0.97	3.26	0.44	0.44	0.025	0.47
Diesel-Fired Emergency Generator	23.08	12.62	1.44	1.44	7.438E-04	23.08
Diesel Fire Pump	1.96	1.72	0.20	0.20	1.01E-04	1.96
Fuel Gas Heater	0.57	1.92	0.39	0.39	0.01	0.28

(1) Hourly emission rates/calculations provided by Dominion and/or based on vendor information.

(2) Hourly emission rates represent the operation of a single cell of inlet turbine chiller.

Combined-cycle turbines with HRSG are considered fossil fuel-fired steam electric plants (one of the “major stationary source” categories identified in 9 VAC 5-80-1615), and are therefore subject to the PSD permitting requirements if the facility’s Potential to Emit (PTE) exceeds 100 tons or more per year of any regulated pollutant. Each of the three requested scenarios for the Warren County Project will have the potential to emit more than 100 tons per year of any regulated NSR pollutant, therefore, this project is a major stationary source subject to a permit under the provisions of 9 VAC 5 Chapter 80, Article 8 (PSD).

Table 2-2 lists the PSD Significant Emission Rates (SERs). For each of the three turbine configurations, the expected annual emission rate from the proposed project was compared to the PSD SERs to determine the PSD applicability. The expected annual emission rate for each of the turbine configurations is discussed in the following sub-sections.

Table 2-2 PSD Significant Emission Rates

Pollutant	Emission Rate (Tons Per Year)
Carbon monoxide	100
Nitrogen oxides	40
Sulfur Dioxides	40
Particulate Matter (PM)	25
Fine Particulate matter (PM_{10})	15
Particulate Matter less than 2.5 microns ($PM_{2.5}$)	10
Ozone	40 of volatile organic compounds
Lead	0.6
Fluorides	3
Sulfuric acid mist	7
Total reduced sulfur	10
Source: 9 VAC 5-80-1615	

2.3.1.1 Siemens SGT6-5000F Turbines

Table 2-3 lists the expected maximum hourly emission rates of criteria pollutants from the proposed Siemens SGT6-5000F combined-cycle combustion turbines. The combustion turbine data shown in Table 2-3 reflects the maximum hourly emissions for the Project over a range of operating loads and ambient operating conditions as summarized below:

<u>Siemens SGT6-5000F Combined-Cycle Combustion Turbines – Natural Gas Operations</u>

- 4 operating loads (100% w/Duct Firing, 100%, 80%, 60%)
- 3 ambient temperatures (100°F, 59°F, 0°F)

Table 2-3 Preliminary Maximum Hourly Emission Rates of Criteria Pollutants from Siemens 5000F Combined-Cycle Combustion Turbines

Pollutant	Combustion Turbine Maximum Hourly Emission Rates (lb/hr) (1) (2)
NO_X	19.90
CO	10.47
PM_{10}	15.93
$PM_{2.5}$	15.93
SO_2	0.77
VOC	5.48
Pb	Negligible
H_2SO_4 Mist	0.69

(1) Hourly Emission rates/calculations provided by Dominion and/or based on vendor information. Emission rates presented in this table are preliminary and are subject to change prior to permit application submittal.

(2) Pollutant emission rates shown represent maximum operation of a single combined-cycle combustion turbine over the proposed 60% to 100% load operating range and for all ambient temperatures.

Table 2-4 Potential Annual Emission Rate of Criteria Pollutants for Proposed Project – Siemens SGT6-5000F Turbines

Pollutant	Annual Emission Rate (1) (2) (Tons Per Year)
NO_x	257.23
CO	247.84
PM_{10}	190.43
$PM_{2.5}$	189.96
SO_2	9.64
VOC	91.35
Pb	0.10
H_2SO_4 Mist	7.44

(1) Potential annual emissions of criteria pollutants for proposed project are based on the following:
- The annual emission rate for the combined-cycle turbines is based on 6,000 hours per year with duct firing and 2,760 hours per year without duct firing.
- The inlet turbine chiller will operate up to 8,760 hours per year.
- The auxiliary boiler will operate up to 8,760 hours per year.
- The diesel fired fire-water pump and diesel emergency generator will be operated no more than 500 hours per year each.
- The fuel gas heater will operate up to 8,760 hours per year.

(2) Annual emissions were calculated using the highest hourly emission rates over all ambient temperatures and operating modes, where applicable.

Annual emissions were calculated using the highest hourly emission rates over all ambient temperatures and operating modes, where applicable.

Table 2-4 indicates that the proposed project is a major source under the Federal New Source Review program since potential emissions from the primary sources will be greater than the 100 ton per year PSD major source threshold for CO, NO_2, $PM_{2.5}$ and PM_{10}. Emissions for pollutants not exceeding the 100 ton per year threshold were compared to the PSD SERs to determine if additional pollutants are subject to PSD review. Based on this review, the proposed Project is also subject to PSD review for VOC and H_2SO_4. Due to the proximity of the project site to a Class I area (within 10 km), there is an additional trigger for PSD review, if "any emissions rate or any net emissions increase associated with a major stationary source or major modification, which could construct within 10 km of a Class I area, and have an impact on such area equal to or greater than 1 $\mu g/m^3$ (24-hour average)." This trigger could potentially affect SO_2 and Pb. Preliminary modeling indicates that the 24-hour SO_2 impact in the Shenandoah National Park will be well below 1 $\mu g/m^3$ (and the Pb emission rate is well below this level). The modeling demonstration in the Class I area for SO_2 will demonstrate this point. Therefore, PSD review is not triggered for either SO_2 or Pb. The proposed facility will be subject to PSD review and applicable PSD modeling for NO_2, CO and PM_{10}. A separate $PM_{2.5}$ analysis is addressed in Section 5.5.

2.3.1.2 Mitsubishi M501GAC Turbines

Table 2-5 lists the expected maximum hourly emission rates of criteria pollutants from the proposed Mitsubishi M501GAC combined-cycle combustion turbines. The combustion turbine data shown in Table 2-5 reflects the maximum hourly emissions for the proposed Project over a range of operating loads and ambient operating conditions as summarized below:

<u>Mitsubishi M501GAC Combined-Cycle Combustion Turbines – Natural Gas Operations</u>

- 4 operating loads (100% w/Duct Firing, 100%, 75%, 60%)
- 3 ambient temperatures (100°F, 59°F, 0°F)

Table 2-5 Preliminary Maximum Hourly Emission Rates of Criteria Pollutants from Mitsubishi M501GAC Combined-Cycle Combustion Turbines

Pollutant	Combustion Turbine Maximum Hourly Emission Rates (lb/hr) (1) (2)
NO_x	25.32
CO	17.41
PM_{10}	21.16
$PM_{2.5}$	21.16
SO_2	0.98
VOC	6.14
Pb	Negligible
H_2SO_4 Mist	0.88

(1) Hourly Emission rates/calculations provided by Dominion and/or based on vendor information. Emission rates presented in this table are preliminary and are subject to change prior to permit application submittal.

(2) Pollutant emission rates shown represent maximum operation of a single combined-cycle combustion turbine over the proposed 60% to 100% load operating range and for all ambient temperatures.

Table 2-6 Potential Annual Emission Rate of Criteria Pollutants for Proposed Project – Mitsubishi M501GAC Turbines

Pollutant	Annual Emission Rate (1) (2) (Tons Per Year)
NO_x	328.39
CO	392.52
PM_{10}	258.13
$PM_{2.5}$	257.66
SO_2	12.39
VOC	305.16
Pb	0.11
H_2SO_4 Mist	9.55

(1) Potential annual emissions of criteria pollutants for proposed project are based on the following:
- The annual emission rate for the combined-cycle turbines is based on 6,000 hours per year with duct firing and 2,760 hours per year without duct firing.
- The inlet turbine chiller will operate up to 8,760 hours per year.
- The auxiliary boiler will operate up to 8,760 hours per year.
- The diesel fired fire-water pump and diesel emergency generator will be operated no more than 500 hours per year each.
- The fuel gas heater will operate up to 8,760 hours per year.

(2) Annual emissions were calculated using the highest hourly emission rates over all ambient temperatures and operating modes, where applicable.

Annual emissions were calculated using the highest hourly emission rates over all ambient temperatures and operating modes, where applicable.

Table 2-6 indicates that the proposed project is a major source under the Federal New Source Review program since potential emissions from the primary sources will be greater than the 100 ton per year PSD major source threshold for CO, NO_2, $PM_{2.5}$ and PM_{10}. Emissions for pollutants not exceeding the 100 ton per year threshold were compared to the PSD SERs to determine if additional pollutants are subject to PSD review. Based on this review, the proposed Project is also subject to PSD review for VOC and H_2SO_4. Due to the proximity of the project site to a Class I area (within 10 km), there is an additional trigger for PSD review, if “any emissions rate or any net emissions increase associated with a major stationary source or major modification, which could construct within 10 km of a Class I area, and have an impact on such area equal to or greater than 1 $\mu g/m^3$ (24-hour average)”. This trigger could potentially affect SO_2 and Pb. Preliminary modeling indicates that the 24-hour SO_2 impact in the Shenandoah National Park will be well below 1 $\mu g/m^3$ (and the Pb emission rate is well below this level). The modeling demonstration in the Class I area for SO_2 will demonstrate this point. Therefore, PSD review is not triggered for either SO_2 or Pb. The proposed facility will be subject to PSD review and applicable PSD modeling for NO_2, CO and PM_{10}. A separate $PM_{2.5}$ analysis is addressed in Section 5.5.

2.3.1.3 GE 7FA05 Turbines

Table 2-7 lists the expected maximum hourly emission rates of criteria pollutants from the proposed GE 7FA05 combined-cycle combustion turbines. The combustion turbine data shown in Table 2-7 reflects the maximum hourly emissions for the proposed Project over a range of operating loads and ambient operating conditions as summarized below:

GE 7FA05 Combined-Cycle Combustion Turbines – Natural Gas Operations

- 4 operating loads (100% w/Duct Firing, 100%, 75%, low load)
- 3 ambient temperatures (100°F, 59°F, 0°F)

Table 2-7 Preliminary Maximum Hourly Emission Rates of Criteria Pollutants from GE 7FA05 Combined-Cycle Combustion Turbines

Pollutant	Combustion Turbine Maximum Hourly Emission Rates (lb/hr) (1) (2)
NO_x	19.81
CO	14.15
PM_{10}	17.93
$PM_{2.5}$	17.93
SO_2	0.77
VOC	6.26
Pb	Negligible
H_2SO_4 Mist	0.69

(1) Hourly Emission rates/calculations provided by Dominion and/or based on vendor information. Emission rates presented in this table are preliminary and are subject to change prior to permit application submittal.

(2) Pollutant emission rates shown represent maximum operation of a single combined-cycle combustion turbine over the proposed low load to 100% load operating range and for all ambient temperatures.

Table 2-8 Potential Annual Emission Rate of Criteria Pollutants for Proposed Project – GE 7FA05 Turbines

Pollutant	Annual Emission Rate [(1) (2)] (Tons Per Year)
NO_x	262.29
CO	258.21
PM_{10}	217.17
$PM_{2.5}$	216.70
SO_2	9.65
VOC	102.51
Pb	0.21
H_2SO_4 Mist	7.41

(1) Potential annual emissions of criteria pollutants for proposed project are based on the following:
- The annual emission rate for the combined-cycle turbines is based on 6,000 hours per year with duct firing and 2,760 hours per year without duct firing.
- The inlet turbine chiller will operate up to 8,760 hours per year.
- The auxiliary boiler will operate up to 8,760 hours per year.
- The diesel fired fire-water pump and diesel emergency generator will be operated no more than 500 hours per year each.
- The fuel gas heater will operate up to 8,760 hours per year.

(2) Annual emissions were calculated using the highest hourly emission rates over all ambient temperatures and operating modes, where applicable.

Annual emissions were calculated using the highest hourly emission rates over all ambient temperatures and operating modes, where applicable.

Table 2-8 indicates that the proposed project is a major source under the Federal New Source Review program since potential emissions from the primary sources will be greater than the 100 ton per year PSD major source threshold for CO, NO_2, $PM_{2.5}$ and PM_{10}. Emissions for pollutants not exceeding the 100 ton per year threshold were compared to the PSD SERs to determine if additional pollutants are subject to PSD review. Based on this review, the proposed Project is also subject to PSD review for VOC and H_2SO_4. Due to the proximity of the project site to a Class I area (within 10 km), there is an additional trigger for PSD review, if “any emissions rate or any net emissions increase associated with a major stationary source or major modification, which could construct within 10 km of a Class I area, and have an impact on such area equal to or greater than 1 $\mu g/m^3$ (24-hour average).” This trigger could potentially affect SO_2 and Pb. Preliminary modeling indicates that the 24-hour SO_2 impact in the Shenandoah National Park will be well below 1 $\mu g/m^3$ (and the Pb emission rate is well below this level). The modeling demonstration in the Class I area for SO_2 will demonstrate this point. Therefore, PSD review is not triggered for either SO_2 or Pb. The proposed facility will be subject to PSD review and applicable PSD modeling for NO_2, CO and PM_{10}. A separate $PM_{2.5}$ analysis is addressed in Section 5.5.

2.3.2 Toxic Air Pollutant Emissions

In addition to predicting the ambient air concentrations of criteria pollutants, the concentrations of other pollutants from the Warren County Project emission sources regulated under VADEQ air toxics program will be evaluated.

The emissions will be estimated using emission factors (AP-42), vendor data or other reference documents. The potential emissions will be compared to each pollutant's exemption level. Based on the guidance received from VA DEQ, Valley Regional Office (VRO) will be contacted to determine the sources that are subject to 9 VAC 5-60-300 C 7. A modeling analysis will be performed for the pollutants which are above the exemption level and the sources that are subject to the regulation. The modeled concentrations will be compared to the corresponding pollutant Significant Ambient Air Concentration (SAAC).

3.0 Air Quality Impact Assessment Methodology

The dispersion modeling analyses conducted for this project will adhere to the United States Environmental Protection Agency (EPA)"Guideline on Air Quality Models" (GAQM, which is contained in 40 CFR Part 51, Appendix W) and direction received from the VA DEQ Modeling Section. The following sections present the source data to be modeled, the proposed procedure for assessing ambient air impacts from the proposed project's emissions and the standards to which the predicted impacts will be compared.

3.1 Background Discussion

The proposed project will be a major source for CO, NO_2, $PM_{2.5}$, and PM_{10} for all the three turbine configurations as discussed in Section 2.3 of the document; therefore, PSD review and associated dispersion modeling analysis will be required for these pollutants. Modeling analyses to be performed will evaluate compliance with applicable PSD increments for these pollutants. In addition, compliance with the National Ambient Air Quality Standards (NAAQS) will also be evaluated.

Based on the current project design, the natural gas-fired combustion turbines are the primary sources of pollutant emissions at this plant. Much smaller quantities of criteria pollutants are emitted from the inlet turbine chiller, auxiliary boiler, diesel-fired emergency generator, diesel-fired fire water pump and fuel gas heater.

As will be discussed in the following sections of this protocol, the dispersion modeling for this project will be conducted in a manner that utilizes the worst-case operating conditions associated with the ambient temperature range in an effort to predict the highest impact for each averaging period. Maximum predicted impacts from the worst case scenarios will be compared to the Significant Impact Levels (SILs), as presented in Table 3-1. For those pollutants which have maximum predicted impacts below the applicable SIL, no additional analysis will be necessary since, by definition, the plant would not cause or contribute to a NAAQS violation or and exceedance of the PSD increment for that pollutant. If modeling indicates that SILs for some pollutants and averaging periods are exceeded, then a cumulative impact assessment will be undertaken based on the corresponding worst-case operating conditions. The results of the cumulative modeling will be analyzed for comparison to Federal and state ambient air quality standards and PSD increments, if applicable.

Table 3-1 Criteria Pollutant Significant Impact Levels

Pollutant	Averaging Time				
	Annual	24-hour	8-hour	3-hour	1-hour
NO_2	1 $\mu g/m^3$	-	-	-	-
CO	-	-	500 $\mu g/ m^3$	-	2000 $\mu g/ m^3$
PM_{10}	1 $\mu g/ m^3$	5 $\mu g/ m^3$	-	-	-
Source: 9 VAC 5-80-1715 B.1					

3.2 Source Data

The air dispersion modeling analysis will be conducted with emission rates and flue gas exhaust characteristics (flow rate and temperature) that are expected to represent the worst-case parameters among the range of possible values the for the three turbine configurations considered for the proposed project. As mentioned previously, the same auxiliary equipment is being proposed for either of the three turbine configurations. Table 3-2 provides the stack parameters and criteria pollutant emission rates for the inlet turbine chillers, auxiliary boiler, diesel-fired emergency generator, diesel-fired fire water pump and the fuel gas heater.

Since the performance data for the auxiliary equipment are not affected by ambient conditions, only one set of parameters will be modeled (e.g., stack parameters and emission rates associated with 100% load). The inlet turbine chillers, auxiliary boiler and the fuel gas heater are expected to operate 8,760 hours per year. The diesel fired fire-water pump and diesel-fired emergency generator will be operated no more than 500 hours per year each.

Table 3-2 Source Parameters and Criteria Pollutant Emission Rates[(1)] For the Auxiliary Equipment

Source ID	Stack Height (ft)	Stack Diameter (ft)	Exit Temp. (°F)	Exit Velocity (fps)	Hourly Emissions (lb/hr)				
					NO_X	CO	PM_{10}	$PM_{2.5}$	SO_2
Inlet Turbine Chiller1*									
CHLR1	42.88	12.00	70.00	24.50	--	--	5.99E-03	1.84E-05	--
Inlet Turbine Chiller2*									
CHLR2	42.88	12.00	70.00	24.50	--	--	5.99E-03	1.84E-05	--
Inlet Turbine Chiller3*									
CHLR3	42.88	12.00	70.00	24.50	--	--	5.99E-03	1.84E-05	--
Auxiliary Boiler									
AUX_BLR	115.00	3.00	300.00	61.00	0.97	3.26	0.44	0.44	0.03
Diesel-Fired Emergency Generator									
DSL_GEN	20.00	1.23	987.00	135.00	23.08	12.62	1.44	1.44	0.00074
Diesel-Fired Fire Water Pump Engine									
FWP	20.00	0.44	845.00	135.00	1.96	1.72	0.20	0.20	0.00010
Fuel Gas Heater									
FGH	45.00	3.33	300	32.00	0.57	1.92	0.39	0.39	0.02

(1) Data provided by Dominion. Source parameters and emission rates presented in this table are preliminary and are subject to change prior to permit application submittal.

*The hourly emissions represent the emissions from a single cell of the 6-cell inlet turbine chiller.

The stack parameters and the criteria pollutant emissions for each of the three turbine configurations are presented in the following sub-sections.

3.2.1 Siemens SGT6-5000F Combined-Cycle Combustion Turbines

3.2.1.1 Normal Operation

Since turbine emission rates and flue gas characteristics for a given turbine load vary as a function of ambient temperature, data was derived for the following ambient temperatures and load scenarios for the proposed Siemens SGT6-5000F turbines:

<u>Siemens SGT6-5000F Combined-Cycle Combustion Turbines – Natural Gas Operations</u>

- 4 operating loads (100% w/ Duct Firing, 100%, 80%, 60%)
- 3 ambient temperatures (100°F, 59°F, 0°F)

A summary of the combined-cycle exhaust data and emission rates for the PSD-regulated pollutants for each ambient temperature and operating load during natural gas combustion is provided in Table 3-3. The proposed Siemens SGT6-5000F turbines are each rated at a maximum capacity of 2,748 MMBtu/hr at 0°F. (2,248 MMBtu/hr rating for the combustion turbines and 500 MMBtu/hr rating for the duct burners).

Based on current project design parameters, Dominion intends to apply for a permit that will allow unrestricted annual operation (8,760 hours per year) of each combined-cycle combustion turbine.

In order to conservatively calculate ground-level concentrations, a composite “worst-case” set of emission parameters will be used in the modeling in an initial approach. If the conservative assumptions need to be refined in additional modeling, we will proceed to that step. For each combined-cycle operating load in the initial modeling, the highest pollutant-specific emission rate coupled with the lowest exhaust temperature and exhaust flow rate will be selected. Table 3-4 summarizes the worst-case emission parameters for the Siemens SGT6-5000F combined-cycle operating loads firing natural gas.

Table 3-3 Source Parameters and Criteria Pollutant Emission Rates[1] Natural Gas-Fired Siemens SGT6-5000F Combined-Cycle Combustion Turbine Operation

Scenario[2]	Heat Input (MMBtu/hr)	Stack Height (ft)	Stack Dia. (ft)	Exit Temp. (°F)	Exit Velocity (fps)	Hourly Emissions[3]				
						NO_X	CO	PM_{10}	$PM_{2.5}$	SO_2
100% load with Duct Firing @ 0°F	***2748***	175.0	19.0	200.20	75.15	***19.90***	***10.47***	***15.93***	***15.93***	***0.77***
100% load with Duct Firing @ 59°F	2451	175.0	19.0	195.10	66.50	17.75	10.08	15.83	15.83	0.69
100% load with Duct Firing and Inlet Chiller @ 59°F	2500	175.0	19.0	196.20	67.96	18.11	10.15	15.85	15.85	0.70
100% load with Duct Firing @ 100°F	2230	175.0	19.0	197.90	60.15	16.15	9.79	15.75	15.75	0.62
100% load with Duct Firing and Inlet Chiller @ 100°F	2502	175.0	19.0	202.60	68.62	18.12	10.15	15.85	15.85	0.70
100% load @ 0°F	***2248***	175.0	19.0	206.30	75.21	***16.28***	***2.97***	***10.40***	***10.40***	***0.63***
100% load @ 59°F	1951	175.0	19.0	***201.60***	66.52	14.13	2.58	10.35	10.35	0.55
100% load with Inlet Chiller @ 59°F	2000	175.0	19.0	202.20	67.93	14.49	2.65	10.36	10.36	0.56
100% load @ 100°F	1730	175.0	19.0	201.80	***59.87***	12.53	2.29	10.31	10.31	0.48
100% load with Inlet Chiller @ 100°F	2002	175.0	19.0	208.30	68.57	14.50	2.65	10.36	10.36	0.56
80% load @ 0°F	***1845***	175.0	19.0	200.70	62.29	***13.37***	***2.44***	***10.33***	***10.33***	***0.52***
80% load @ 59°F	1631	175.0	19.0	195.90	56.61	11.81	2.16	10.29	10.29	0.46
80% load @ 100°F	1459	175.0	19.0	***195.90***	***51.54***	10.57	1.93	10.26	10.26	0.41
60% load @ 0°F	***1496***	175.0	19.0	194.10	52.41	***10.84***	***4.95***	***10.27***	***10.27***	***0.42***
60% load @ 59°F	1329	175.0	19.0	190.00	47.91	9.62	4.39	10.24	10.24	0.37
60% load @ 100°F	1197	175.0	19.0	***190.00***	***43.87***	8.67	3.96	10.21	10.21	0.33

(1) Data provided by Dominion. Source parameters and emission rates presented in this table are preliminary and are subject to change prior to permit application submittal.

(2) Data presented are for four operating loads/conditions at three ambient temperatures

(3) Hourly emissions reflect operation of a Siemens SGT6-5000F combined-cycle combustion turbine firing pipeline natural gas only.

Table 3-4 Worst Case Data (1) for Proposed Natural Gas-Fired SGT6-5000F Combined-Cycle Combustion Turbine Operation

Parameter		Value			
Load (%)		**100 w/ Duct Firing**	**100**	**80**	**60**
Stack Height (ft)		175.0	175.0	175.0	175.0
Stack Diameter (ft)		19.0	19.0	19.0	19.0
Exit Temperature (°F)		195.10	201.60	195.90	190.00
Exit Velocity (ft/sec)		60.15	59.87	51.54	43.87
Heat Input (MMBtu/hr)		2748	2248	1845	1496
Pollutant Emissions Per Combustion Turbine(lb/hr)	**SO_2**	0.77	0.63	0.52	0.42
	PM_{10}	15.93	10.40	10.33	10.27
	$PM_{2.5}$	15.93	10.40	10.33	10.27
	NO_X	19.90	16.28	13.37	10.84
	CO	10.47	2.97	2.44	4.95

(1) The values in the table represent the worst-case stack parameters and the emission rates for the four operating loads taken from the Table 3-3 (bold and italicized)

3.2.1.2 Startup/Shutdown Operations

Annual emissions resulting from start-up/shutdown operations for the proposed turbines are based on 174.5 hot starts/year, 15 warm starts/year, and 6.5 cold starts/year. For each hot start, the turbines are offline for 4 hours, for each warm start, the turbines are offline for 40 hours and for each cold start, the turbines are offline for 72 hours. Under this operating scenario, it is estimated that the turbines will remain offline for 1,766 hours/year.

Annual emissions for the three combustion turbines were calculated based on the maximum of either 8,760 hr/year of continuous operation or a mix of continuous operation and the maximum number of startup/shutdown events. Table 3-5 presents the annual emissions (tons/year) of criteria pollutants for the three turbines arranged in a 3x3x1 configuration.

Table 3-5 Worst Case Data for Proposed Natural Gas-Fired SGT6-5000F Combined-Cycle Combustion Turbine Operation

Parameter	CT w/DB (lb/hr)	CT w/out DB (lb/hr)	Potential Annual Emission Rates (Per Turbine) (TPY)				3x3x1 Configuration (TPY)
Operating Hours (hrs/yr)	6,000	2,760	**Based on DB & CT Only Operating Hour Limits**	**Based on CT Only Year-Round**	**W/ SUSD**	**Worst-Case Annual Emissions**	**Worst-Case Annual Emissions**
NO_X	19.90	16.28	82.17	71.30	70.24	82.17	246.50
CO	10.47	4.95	38.25	21.67	76.50	76.50	229.50
VOC	5.48	1.98	19.18	8.68	27.63	27.63	82.88
PM_{10}	15.93	10.40	62.14	45.56	<62.14	62.14	186.43
$PM_{2.5}$	15.93	10.40	62.14	45.56	<62.14	62.14	186.43
SO_2	0.77	0.63	3.17	2.75	<3.17	3.17	9.52

Notes:

(1). Duct burner capacity estimated at 500 MMBtu/hr (at 100% load).

(2). Hourly emission estimates are based on worst-case ambient conditions (i.e., temperature, % relative humidity) at normal operations.

(3). For "Annual emissions with DB Firing at Operating Hour Limit", emission estimates were calculated as follows:

Annual Emissions (ton/yr) = [Pollutant Emission Rate, CT w/DB (lb/hr) x Operating Hours, CT w/DB (hr/yr) + Pollutant Emission Rate, CT only (lb/hr) x Operating Hours, CT only (hr/yr)] / (2000 lb / ton)

(4). For "annual emissions with no DB firing", emission estimates for the natural gas firing (CT only) were based on 8760 operating hours per year.

The Table 3-5 shows that the emissions from the proposed Siemens SGT6-5000F combustion turbines during the normal operation represent the worst-case scenario for the pollutants NO_X, PM_{10}, $PM_{2.5}$ and SO_2. However, the emissions for the pollutants CO and VOC are higher with the startup/shutdown operations. Therefore, a startup/shutdown modeling analysis will be performed only for CO.

3.2.2 Mitsubishi M501GAC Combined-Cycle Combustion Turbines

3.2.2.1 Normal Operation

Since turbine emission rates and flue gas characteristics for a given turbine load vary as a function of ambient temperature, data was derived for the following ambient temperatures and load scenarios for the proposed Mitsubishi M501GAC combustion turbines:

Mitsubishi M501GAC Combined-Cycle Combustion Turbines – Natural Gas Operations

- 4 operating loads (100% w/ Duct Firing, 100%, 75%, 60%)
- 3 ambient temperatures (100°F, 59°F, 0°F)

A summary of the combined-cycle exhaust data and emission rates for the PSD-regulated pollutants for each ambient temperature and operating load during natural gas combustion is provided in Table 3-6. The proposed Mitsubishi M501GAC turbines are each rated at a maximum capacity of 3,496 MMBtu/hr at 0°F (2,996 MMBtu/hr rating for the combustion turbines and 500 MMBtu/hr rating for the duct burners).

Based on current project design parameters, Dominion intends to apply for a permit that will allow unrestricted annual operation (8,760 hours per year) of each combined-cycle combustion turbine.

In order to conservatively calculate ground-level concentrations, a composite "worst-case" set of emission parameters will be used in the modeling in an initial approach. If the conservative assumptions need to be refined in additional modeling, we will proceed to that step. For each combined-cycle operating load in the initial modeling, the highest pollutant-specific emission rate coupled with the lowest exhaust temperature and exhaust flow rate will be selected. Table 3-7 summarizes the worst-case emission parameters for the Mitsubishi M501GAC combined-cycle operating loads firing natural gas.

Table 3-6 Source Parameters and Criteria Pollutant Emission Rates[1] Natural Gas-Fired Mitsubishi M501GAC Combined-Cycle Combustion Turbine Operation

Scenario[2]	Heat Input (MMBtu/hr)	Stack Height (ft)	Stack Dia. (ft)	Exit Temp. (°F)	Exit Velocity (fps)	Hourly Emissions[3]				
						NO_X	CO	PM_{10}	$PM_{2.5}$	SO_2
100% load with Duct Firing @ 0°F	***3496***	175.0	22.0	195.80	70.44	***25.32***	***17.41***	***21.16***	***21.16***	***0.98***
100% load with Duct Firing @ 59°F	3108	175.0	22.0	***191.20***	62.73	22.51	16.12	19.09	19.09	0.87
100% load with Duct Firing and Inlet Chiller @ 59°F	3170	175.0	22.0	192.30	63.96	22.96	16.33	19.42	19.42	0.89
100% load with Duct Firing @ 100°F	2841	175.0	22.0	195.30	***57.83***	20.57	15.24	17.66	17.66	0.79
100% load with Duct Firing and Inlet Chiller @ 100°F	3170	175.0	22.0	199.30	64.65	22.96	16.33	19.42	19.42	0.89
100% load @ 0°F	***2996***	175.0	22.0	202.10	70.64	***21.70***	***9.91***	***15.51***	***15.51***	***0.84***
100% load @ 59°F	2608	175.0	22.0	***197.70***	62.89	18.89	8.62	13.51	13.51	0.73
100% load with Inlet Chiller @ 59°F	2670	175.0	22.0	198.40	64.09	19.34	8.83	13.83	13.83	0.75
100% load @ 100°F	2341	175.0	22.0	199.60	***57.74***	16.95	7.74	12.12	12.12	0.65
100% load with Inlet Chiller @ 100°F	2670	175.0	22.0	205.10	64.74	19.34	8.83	13.83	13.83	0.75
75% load @ 0°F	***2302***	175.0	22.0	194.60	56.78	***16.67***	***7.61***	***11.92***	***11.92***	***0.64***
75% load @ 59°F	2052	175.0	22.0	***191.50***	52.08	14.86	6.78	10.63	10.63	0.57
75% load @ 100°F	1874	175.0	22.0	192.90	***48.32***	13.57	6.20	9.70	9.70	0.52
60% load @ 0°F	***1966***	175.0	22.0	187.20	47.01	***14.24***	***6.50***	***10.18***	***10.18***	***0.55***
60% load @ 59°F	1770	175.0	22.0	***185.00***	43.60	12.82	5.85	9.17	9.17	0.50
60% load @ 100°F	1627	175.0	22.0	185.70	***41.16***	11.78	5.38	8.43	8.43	0.46

(1) Data provided by Dominion. Source parameters and emission rates presented in this table are preliminary and are subject to change prior to permit application submittal.

(2) Data presented are for four operating loads/conditions at three ambient temperatures

(3) Hourly emissions reflect operation of a Mitsubishi M501GAC combined-cycle combustion turbine firing pipeline natural gas only.

Table 3-7 Worst Case Data [(1)] for Proposed Natural Gas-Fired Mitsubishi M501GAC Combined-Cycle Combustion Turbine Operation

Parameter		Value			
Load (%)		**100 w/ Duct Firing**	**100**	**75**	**60**
Stack Height (ft)		175.0	175.0	175.0	175.0
Stack Diameter (ft)		22.0	22.0	22.0	22.0
Exit Temperature (°F)		191.20	197.70	191.50	185.00
Exit Velocity (ft/sec)		57.83	57.74	48.32	41.16
Heat Input (MMBtu/hr)		3496	2996	2302	1966
Pollutant Emissions Per Combustion Turbine(lb/hr)	**SO_2**	0.98	0.84	0.64	0.55
	PM_{10}	21.16	15.51	11.92	10.18
	$PM_{2.5}$	21.16	15.51	11.92	10.18
	NO_X	25.32	21.70	16.67	14.24
	CO	17.41	9.91	7.61	6.50

(1) The values in the table represent the worst-case stack parameters and the emission rates for the four operating loads taken from the Table 3-5 (bold and italicized)

3.2.2.2 Startup/Shutdown Operations

Annual emissions resulting from start-up/shutdown operations for the proposed turbines are based on 174.5 hot starts/year, 15 warm starts/year, and 6.5 cold starts/year. For each hot start, the turbines are offline for 4 hours, for each warm start, the turbines are offline for 40 hours and for each cold start, the turbines are offline for 72 hours. Under this operating scenario, it is estimated that the turbines will remain offline for 1,766 hours/year.

Annual emissions for the three combustion turbines were calculated based on the maximum of either 8,760 hr/year of continuous operation or a mix of continuous operation and the maximum number of startup/shutdown events. Table 3-8 presents the annual emissions (tons/year) of criteria pollutants for the three turbines arranged in a 3x3x1 configuration.

Table 3-8 Worst Case Data for Proposed Natural Gas-Fired Mitsubishi M501GAC Combined-Cycle Combustion Turbine Operation

Parameter	CT w/DB (lb/hr)	CT w/out DB (lb/hr)	Potential Annual Emission Rates (Per Turbine) (TPY)				3x3x1 Configuration (TPY)
Operating Hours (hrs/yr)	6,000	2,760	Based on DB & CT Only Operating Hour Limits	Based on CT Only Year-Round	W/ SUSD	Worst-Case Annual Emissions	Worst-Case Annual Emissions
NO_X	25.32	21.70	105.90	95.03	92.84	105.90	317.69
CO	17.41	9.91	65.88	43.38	124.72	124.72	374.17
VOC	6.14	2.64	22.07	11.57	98.91	98.91	296.72
PM_{10}	21.16	15.51	84.89	67.95	<84.89	84.89	254.67
$PM_{2.5}$	21.16	15.51	84.89	67.95	<84.89	84.89	254.67
SO_2	0.98	0.84	4.09	3.67	<4.09	4.09	12.27

Notes:

(1). Duct burner capacity estimated at 500 MMBtu/hr (at 100% load).

(2). Hourly emission estimates are based on worst-case ambient conditions (i.e., temperature, % relative humidity) at normal operations.

(3). For "Annual emissions with DB Firing at Operating Hour Limit", emission estimates were calculated as follows:

Annual Emissions (ton/yr) = [Pollutant Emission Rate, CT w/DB (lb/hr) x Operating Hours, CT w/DB (hr/yr) + Pollutant Emission Rate, CT only (lb/hr) x Operating Hours, CT only (hr/yr)] / (2000 lb / ton)

(4). For "annual emissions with no DB firing", emission estimates for the natural gas firing (CT only) were based on 8760 operating hours per year.

Table 3-8 shows that the emissions from the proposed Mitsubishi M501GAC combustion turbines during the normal operation represent the worst-case scenario for the pollutants NO_X, PM_{10}, $PM_{2.5}$ and SO_2. However, the emissions for the pollutants CO and VOC are higher with the startup/shutdown operations. Therefore, a startup/shutdown modeling analysis will be performed only for CO.

3.2.3 GE 7FA05 Combined-Cycle Combustion Turbines

3.2.3.1 Normal Operation

Since turbine emission rates and flue gas characteristics for a given turbine load vary as a function of ambient temperature, data was derived for the following ambient temperatures and load scenarios for the proposed GE 7FA05 combustion turbines:

GE 7FA05 Combined-Cycle Combustion Turbines – Natural Gas Operations

- 4 operating loads (100% w/ Duct Firing, 100%, 75%, low load)
- 3 ambient temperatures (100°F, 59°F, 0°F)

A summary of the combined-cycle exhaust data and emission rates for the PSD-regulated pollutants for each ambient temperature and operating load during natural gas combustion is provided in Table 3-9. The proposed GE 7FA05 turbines are rated at a maximum capacity of 2,735 MMBtu/hr at 0°F (2,235 MMBtu/hr rating for just the combustion turbines and 500 MMBtu/hr rating for the duct burners).

Based on current project design parameters, Dominion intends to apply for a permit that will allow unrestricted annual operation (8,760 hours per year) of each combined-cycle combustion turbine.

In order to conservatively calculate ground-level concentrations, a composite "worst-case" set of emission parameters will be used in the modeling in an initial approach. If the conservative assumptions need to be refined in additional modeling, we will proceed to that step. For each combined-cycle operating load in the initial modeling, the highest pollutant-specific emission rate coupled with the lowest exhaust temperature and exhaust flow rate will be selected. Table 3-10 summarizes the worst-case emission parameters for the GE 7FA05 combined-cycle operating loads firing natural gas.

Table 3-9 Source Parameters and Criteria Pollutant Emission Rates[1] Natural Gas-Fired GE GA 7FA05 Combined-Cycle Combustion Turbine Operation

Scenario[2]	Heat Input (MMBtu/hr)	Stack Height (ft)	Stack Dia. (ft)	Exit Temp. (°F)	Exit Velocity (fps)	Hourly Emissions[3]				
						NO_X	CO	PM_{10}	$PM_{2.5}$	SO_2
100% load with Duct Firing @ 0°F	***2735***	175.0	19.0	194.20	73.84	***19.81***	***14.15***	***17.93***	***17.93***	***0.77***
100% load with Duct Firing @ 59°F	2517	175.0	19.0	***190.40***	67.52	18.23	13.50	17.85	17.85	0.70
100% load with Duct Firing and Inlet Chiller @ 59°F	2563	175.0	19.0	191.70	68.82	18.56	13.64	17.87	17.87	0.72
100% load with Duct Firing @ 100°F	2347	175.0	19.0	196.40	***64.43***	17.00	13.00	17.79	17.79	0.66
100% load with Duct Firing and Inlet Chiller @ 100°F	2566	175.0	19.0	199.70	69.66	18.58	13.65	17.87	17.87	0.72
100% load @ 0°F	***2235***	175.0	19.0	201.90	74.08	***16.19***	***6.65***	***12.40***	***12.40***	***0.63***
100% load @ 59°F	2017	175.0	19.0	***197.40***	67.61	14.61	6.00	12.36	12.36	0.56
100% load with Inlet Chiller @ 59°F	2063	175.0	19.0	198.20	68.86	14.94	6.14	12.37	12.37	0.58
100% load @ 100°F	1847	175.0	19.0	200.50	***64.19***	13.38	5.50	12.33	12.33	0.52
100% load with Inlet Chiller @ 100°F	2066	175.0	19.0	204.40	69.52	14.96	6.15	12.37	12.37	0.58
75% load @ 0°F	***1781***	175.0	19.0	192.50	58.11	12.90	5.30	12.32	12.32	0.50
75% load @ 59°F	1651	175.0	19.0	***186.90***	52.75	11.96	4.91	12.30	12.30	0.46
75% load @ 100°F	1537	175.0	19.0	189.40	***50.41***	11.13	4.57	12.28	12.28	0.43
50% load @ 0°F	***1440***	175.0	19.0	185.00	46.11	***10.43***	***4.29***	***12.26***	***12.26***	***0.40***
50% load @ 59°F	1343	175.0	19.0	***184.90***	***45.25***	9.73	4.00	12.24	12.24	0.38
55% load @ 100°F	1323	175.0	19.0	186.40	46.23	9.58	3.94	12.24	12.24	0.37

(1) Data provided by Dominion. Source parameters and emission rates presented in this table are preliminary and are subject to change prior to permit application submittal.

(2) Data presented are for four operating loads/conditions at three ambient temperatures

(3) Hourly emissions reflect operation of a GE 7FA05 combined-cycle combustion turbine firing pipeline natural gas only.

Table 3-10 Worst Case Data [1] for Proposed Natural Gas-Fired GE 7FA05 Combined-Cycle Combustion Turbine Operation

Parameter		Value			
Load (%)		**100 w/ Duct Firing**	**100**	**75**	**Low (50/55)[2]**
Stack Height (ft)		175.0	175.0	175.0	175.0
Stack Diameter (ft)		19.0	19.0	19.0	19.0
Exit Temperature (°F)		190.40	197.40	186.90	184.90
Exit Velocity (ft/sec)		64.43	64.19	50.41	45.25
Heat Input (MMBtu/hr)		2735	2235	1781	1440
Pollutant Emissions Per Combustion Turbine(lb/hr)	**SO_2**	0.77	0.63	0.50	0.40
	PM_{10}	17.93	12.40	12.32	12.26
	$PM_{2.5}$	17.93	12.40	12.32	12.26
	NO_X	19.81	16.19	12.90	10.43
	CO	14.15	6.65	5.30	4.29

(1) The values in the table represent the worst-case stack parameters and the emission rates for the four operating loads taken from the Table 3-7 (bold and italicized)

(2) The minimum load for these turbines is 55% at 100º F. and 50% at 59ºF. and 0ºF.

3.2.3.2 Startup/Shutdown Operations

Annual emissions resulting from start-up/shutdown operations for the proposed turbines are based on 174.5 hot starts/year, 15 warm starts/year, and 6.5 cold starts/year. For each hot start, the turbines are offline for 4 hours, for each warm start, the turbines are offline for 40 hours and for each cold start, the turbines are offline for 72 hours. Under this operating scenario, it is estimated that the turbines will remain offline for 1,766 hours/year.

Annual emissions for the three combustion turbines were calculated based on the maximum of either 8,760 hr/year of continuous operation or a mix of continuous operation and the maximum number of startup/shutdown events. Table 3-11 presents the annual emissions (tons/year) of criteria pollutants for the three turbines arranged in a 3x3x1 configuration.

Table 3-11 Worst Case Data for Proposed Natural Gas-Fired GE 7FA05 Combined-Cycle Combustion Turbine Operation

Parameter	CT w/DB (lb/hr)	CT w/out DB (lb/hr)	Potential Annual Emission Rates (Per Turbine) (TPY)				3x3x1 Configuration (TPY)
Operating Hours (hrs/yr)	6,000	2,760	**Based on DB & CT Only Operating Hour Limits**	**Based on CT Only Year-Round**	**W/ SUSD**	**Worst-Case Annual Emissions**	**Worst-Case Annual Emissions**
NO_X	19.81	16.19	81.77	70.90	83.09	83.09	249.28
CO	14.15	6.65	51.63	29.13	77.31	77.31	231.93
VOC	6.26	2.76	22.58	12.08	30.98	30.98	92.94
PM_{10}	17.93	12.40	70.89	54.31	<70.89	70.89	212.66
$PM_{2.5}$	17.93	12.40	70.89	54.31	<70.89	70.89	212.66
SO_2	0.77	0.63	3.16	2.74	<3.16	3.16	9.48

Notes:

(1). Duct burner capacity estimated at 500 MMBtu/hr (at 100% load).

(2). Hourly emission estimates are based on worst-case ambient conditions (i.e., temperature, % relative humidity) at normal operations.

(3). For "Annual emissions with DB Firing at Operating Hour Limit", emission estimates were calculated as follows:

Annual Emissions (ton/yr) = [Pollutant Emission Rate, CT w/DB (lb/hr) x Operating Hours, CT w/DB (hr/yr) + Pollutant Emission Rate, CT only (lb/hr) x Operating Hours, CT only (hr/yr)] / (2000 lb / ton)

(4). For "annual emissions with no DB firing", emission estimates for the natural gas firing (CT only) were based on 8760 operating hours per year.

Table 3-11 shows that the emissions from the proposed GE 7FA05 combustion turbines during the normal operation represent the worst-case scenario for the pollutants PM_{10}, $PM_{2.5}$ and SO_2. However, the emissions for the pollutants NO_X, CO, and VOC are higher with the startup/shutdown operations. Since NO_2 is an annual average pollutant and the worst-case annual emissions, (TPY) which incidentally includes the startup/shutdown emissions will be modeled, a separate startup/shutdown analysis is not proposed for NO_2. Therefore, a startup/shutdown modeling analysis will be performed only for CO.

3.3 Model Selection

Figure 3-1 shows the location of the project relative to PSD Class I areas. It is noteworthy that while the closest Class I area, Shenandoah National Park, has its closest point within 10 km of the project site, the next closest Class I area, Dolly Sods Wilderness Area, is about 100 km away.

In accordance with the draft FLAG 2009 guidance that is recommended by the Federal Land Managers, we are proposing to exclude from modeling consideration Class I areas that are beyond the FLAG-specified screening distance from the project site. The screening distance is determined by adding the permitted short-term emissions from proposed routine (non-emergency) point sources for SO_2 + NO_x + PM_{10} + H_2SO_4. The sum of these emissions for the scenario with the highest emissions is not expected to exceed 610 tons per year, based upon information provided in Section 2. With a FLAG-prescribed screening distance of 610/10 = 61 km, this results in the determination that only impacts within the Shenandoah National Park should be considered for Air Quality Related Values (AQRVs). In addition, since the peak increment consumption will be modeled within Shenandoah National Park within 50 km from the project site, we conclude that increment consumption modeling as well as AQRV modeling at other Class I areas would not provide higher impacts. Therefore, we propose that to determine the peak project impacts, all Class I modeling can be confined to the portion of Shenandoah National Park within 50 km of the project site. Figure 3-2 shows the proposed receptor coverage of this portion of the park. The receptors are described in more detail in Section 3.6.1.

Figure 3-1 Location of the Proposed Project Relative to Shenandoah National Park

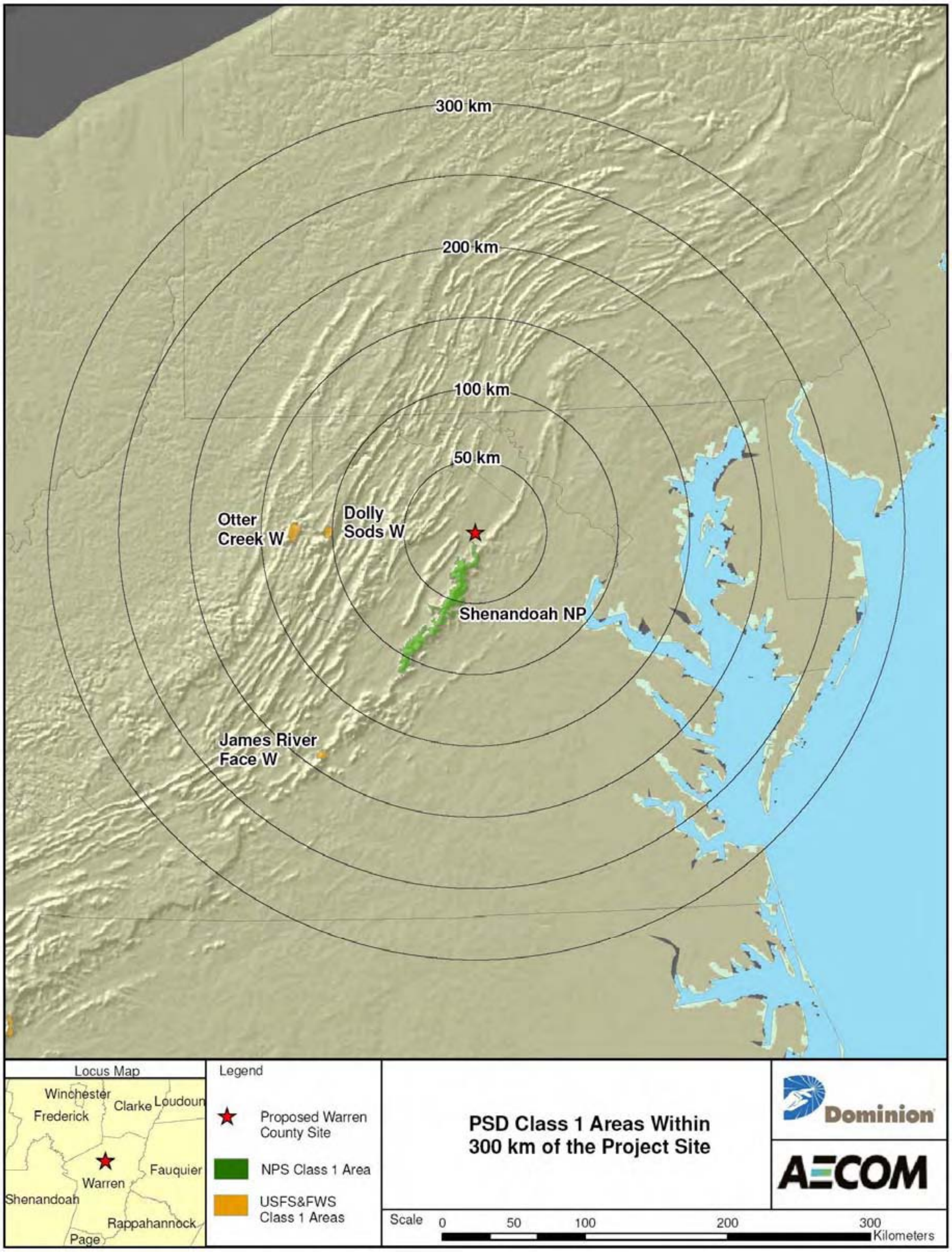
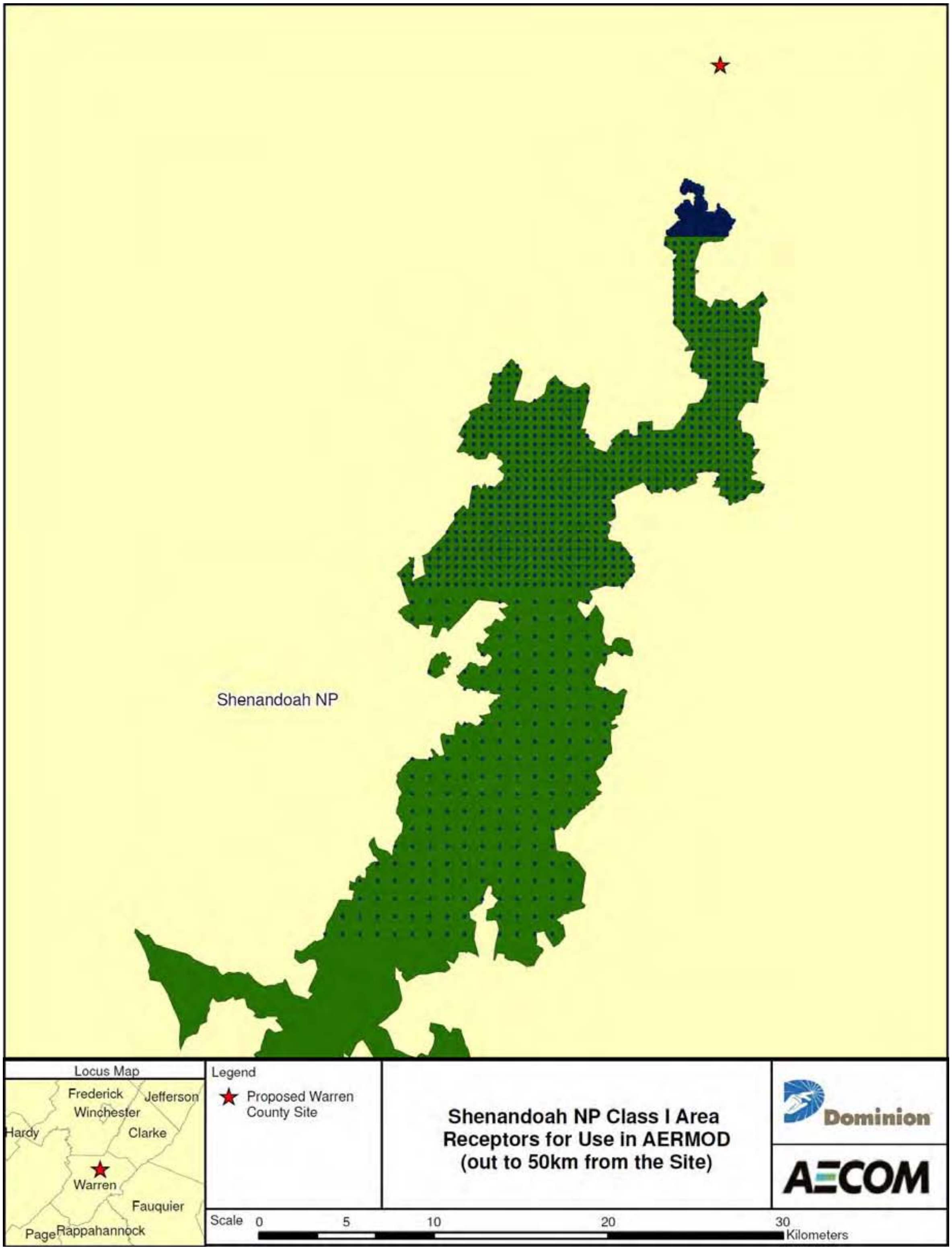


Figure 3-2 Receptor Coverage Proposed for Shenandoah National Park



For the Class I modeling to be conducted in areas within 50 km of the project site, the considerations for the modeling requirements and modeling selection are the same for both Class I and Class II areas. The EPA-preferred dispersion model for areas within 50 km of a proposed emission source is AERMOD. The current versions of the three AERMOD system components, as listed on the EPA dispersion modeling website (http://www.epa.gov/scram001/dispersion_prefrec.htm#aermod), are:

- AERMET version 06341
- AERMAP version 09040, and
- AERMOD version 09292.

For estimating deposition of acidic species associated with emissions of NO_x, AECOM will follow a tiered screening approach. Since the project does not trigger PSD review for SO_2, and the Q/D for SO_2 is well below the FLAG (2008) screening value of 10 (it is, in fact, about 2), a sulfur deposition analysis will not be performed.

For nitrogen deposition associated with NO_x emissions, the Tier 1 Screening method in IWAQM Phase 1 assumes that all NO_x emitted is readily transformed to nitric acid as it enters the atmosphere. The annual nitrogen deposition is then estimated by multiplying the modeled annual average concentration by a deposition velocity of 5 cm/sec. The deposition velocity for nitric acid is more than an order of magnitude greater than that for either NO or NO_2. This simplified screening approach is likely to be overly conservative in this case because only a small fraction of NO_x emissions would be expected to be transformed to nitric acid over nearby Shenandoah National Park.

Therefore, if necessary for nitrogen deposition, a Tier 2 screening assessment will incorporate a conservative, but more realistic estimate of nitric acid formation and deposition. This tiered approach is similar to the tiered approach for computing the NO_2 concentration, for which there are various levels of refinement to predict the conversion of emitted NO to NO_2. The average rate of conversion of NO_x to HNO_3 will be computed by applying the following equation for nitrate transformation rate (k, % per hour), which is used in CALPUFF when the default Mesopuff II chemistry module is selected:

For daytime conditions, the transformation rate (k_3) in %/hr is:

$$k_3 = 1261 [O_3]^{.45} S^{-1.34} [NO_x]^{-0.12}$$

,

where:

S is the stability category (2=A, 6=F),

$[O_3]$ is the ambient ozone concentration (ppm), and

$[NO_x]$ is the average modeled concentration (ppm) within the plume.

For nighttime conditions, the transformation rate (k_4) is 2%/hr.

Section 3.l of the IWAQM Phase 2 document (1998) describes this CALPUFF approach. There is a nighttime chemical transformation of 2% referenced in the IWAQM document, while the daytime chemical transformation varies as a function of stability class as well as ozone and NO_x concentrations. The form of the transformation as (1.-exp(-(rate)*time)) is a classic mathematical approach that is also reflected in the CALPUFF implementation of the MESOPUFF-II chemistry (see CALPUFF code, subroutine CHEMTF, for example). This approach is also documented as Equation 2-32 in the OCD manual supplement available at http://www.epa.gov/scram001/userg/regmod/ocdugsup.pdf.

The implementation of the Tier 2 approach has been proposed as an annual average for several reasons:

- The nighttime rates are constant throughout the year.
- Although the daytime rates vary, the use of the proposed annual average values for the terms in the transformation equation would likely result in a similar outcome to conducting an hourly computation and averaging the hourly deposition rates.
- The hourly stability classes are not directly computed by AERMOD.
- The method does not have a solution (or any predicted concentrations) for hours with calm winds.
- For either an annual or hourly approach, the method must be conducted using an Excel spreadsheet because there is no existing model code for its implementation.

In this formulation, the daytime rate of transformation is inversely proportional to the NO_x concentration in the plume. In applying this equation, we will conservatively use the modeled annual average ground-level NO_x concentration between the plant and the Class I area receptor. Because the ground-level concentration is less than at plume height, the transformation rate will be overestimated. The nitrate species that are formed are typically comprised of ammonium nitrate and nitric acid, with the ratio depending on a variety of factors including the availability of ammonia and ambient temperature. Ammonium nitrate is a fine particulate that has a much lower deposition velocity than nitric acid, which is highly reactive. For this Tier 2 screening assessment, it will be conservatively assumed that all nitrate formed from NO_x emissions is in the form of nitric acid. The background ozone concentration of 0.053 ppm will be used, consistent with annual average measurements in the area and also the plume visibility assessment. An annual average stability of slightly unstable (category C) will be assumed, as a representative for daytime conditions.

In addition, an hourly computation for the refined approach will also be followed. The resulting annual value will be computed as an average over all hourly deposition values available for the year. To remove uncertainty between the results of an annual vs. hourly approach, both the annual and hourly approaches will be applied but limited to the worst-case Shenandoah receptor (highest annual NO_2 concentration) for the worst-case year. For the hourly approach, the following hourly data will be used to implement the refined method:

- hourly ozone data from the Shenandoah Big Meadows CASTNET site (concurrent with the AERMOD meteorological data)
- stability class computed from the AERMET-provided friction velocity and Monin-Obukhov length using the Golder (1972) algorithm to calculate the stability class (code from the AERMOD subroutine “LTOPG” will be used)
- hourly NO_x predictions at the selected receptor
- hourly wind speed from Dulles airport data.

Hourly data for calm wind hours is not available, and will not be included in the annual average.

The day and night deposition of nitrogen due to deposition of HNO_3 will then be conservatively computed according to the following first-order transformation equations:

Daytime Nitrogen deposition = V_d * $[NO_x]_{day}$ * MWR *(1-exp(k_3/100)*X/u_{day})) * (4380*3600 sec/yr)

Nighttime Nitrogen deposition: V_d * $[NO_x]_{night}$ * MWR*(1-exp(2/100)*X/u_{night})) * (4380*3600 sec/yr)

Where:

X= distance (km) to the Class I area receptor,

MWR = ratio of molecular weight of nitrogen and nitrogen dioxide = 0.3125

u = average annual 10-m wind speed (km/hr) for daytime and nighttime hours (Data from the Dulles Airport will be used),

$[NO_x]_{day}$ and $[NO_x]_{night}$ are average modeled daytime and nighttime ground-level concentrations (µg/m^3) along the plume path, and

V_d = the IWAQM nitric acid deposition velocity = 0.05 m/sec.

The conservatively modeled nitrogen deposition will be reported and compared to the conservatively low screening Deposition Analysis Thresholds (NPS, 2002) for the Eastern United States of 0.010 kg/ha/yr.

For plume visibility impacts inside Shenandoah National Park within 50 km, the PLUVUE II model will be used, consistent with past permitting on this project. The procedures for this analysis have been established and agreed to by the National Park Service for the previous permitting of the Warren County project (previously called CPV project) at the same site (see TRC Class I modeling report, 2003). Section 5.1 provides further discussion on this analysis.

3.4 Meteorological Data for AERMOD and PLUVUE

For the previous permitting of the project at this same site, VA DEQ and the National Park Service agreed to the use of five years of National Weather Service data from Dulles International Airport. For this project, we propose to retain the use of the same database, although we discuss alternative approaches in this section, and revised processing procedures due to recent developments in the processing of meteorological data for use in AERMOD. Figure 3-3 shows the locations of the project relative to the airport location. Both sites are located in relatively flat areas, with the overall orientation of distant terrain features consistent from southwest to northeast.

Since the mid-1990s, human weather observers have been replaced in a modernization program sponsored by the National Oceanic and Atmospheric Administration by Automated Surface Observing Stations (ASOS) at airports. Although these observing platforms are more “objective” than humans, they have certain limitations that have led EPA and VADEQ to continue to prefer, in many cases, the use of pre-ASOS data as we are proposing.

- The cloud observations were taken by humans who looked at the entire celestial dome, with no limitation as to the visualization height (unless, of course, obscured by other clouds). The ASOS ceilometers instrument looks straight up and sees only a very small portion of the sky at any one time. It reports a time-averaged tunnel-vision view of the sky. A more serious limitation is that it can only detect clouds as high as 12,000 feet, and reports clear skies if clouds are present at higher levels. This is a serious limitation in the observational ability of the ASOS system.

- The reported ASOS wind speeds are provided to the nearest whole knot after the observed speed value in fractional knots is first truncated by the ASOS system. For example, a wind speed of 3.9 knots is reported as 3 knots. This wind speed bias becomes more serious with lower wind speeds.
- Within each 2-minute period, the ASOS system stores 24 5-second averages. If the extreme wind direction values among the 24 values are more than 60 degrees apart, then the wind direction observation is reported as “variable”, and is essentially missing for purposes of dispersion modeling. The practice of reporting variable wind directions was not used by human observers, who were able to take the wind direction fluctuations into account while using their experienced observing skills to ascertain a mean wind direction.

Due to these important limitations, we are not proposing to use ASOS data, even though it is available at the Leesburg and Winchester, VA airports in addition to Dulles International Airport.

Five years of hourly surface meteorological data will be processed with AERMET, the meteorological preprocessor for AERMOD. The meteorological data required for input to AERMOD will be created with the latest version of AERMET (06341), the meteorological preprocessor, which will utilize hourly surface observations from Dulles International Airport along with concurrent upper air data from Sterling, VA. Table 3-12 gives site locations and information on these data sets. The surface data (wind direction, wind speed, temperature, sky cover, and relative humidity) is measured 6.1 m above ground level. AERMET creates two output files for input to AERMOD:

- SURFACE: a file with boundary layer parameters such as sensible heat flux, surface friction velocity, convective velocity scale, vertical potential temperature gradient in the 500-meter layer above the planetary boundary layer, and convective and mechanical mixing heights. Also provided are values of Monin-Obukhov length, surface roughness, albedo, Bowen ratio, wind speed, wind direction, temperature, and heights at which measurements were taken.
- PROFILE: a file containing multi-level meteorological data with wind speed, wind direction, temperature, sigma-theta (σ_θ) and sigma-w (σ_w) when such data are available. For this application involving representative data from the nearest NWS station, the profile file will contain a single level of wind data (6.1 meters) and the temperature data (2 meters).

In modeling AERMET, the observed airport hourly wind direction will be randomized. Missing morning soundings account for only about 2% of the days, so these will not be filled in by interpolation or substitution.

AERMET requires specification of site characteristics including surface roughness (z_o), albedo (r), and Bowen ratio (B_o). These parameters will be developed according to the guidance provided by US EPA in the recently revised AERMOD Implementation Guide (AIG) (EPA, 2009).

The revised AIG provides the following recommendations for determining the site characteristics:

1. The determination of the surface roughness length should be based on an inverse distance weighted geometric mean for a default upwind distance of 1 kilometer relative to the measurement site. Surface roughness length may be varied by sector to account for

variations in land cover near the measurement site; however, the sector widths should be no smaller than 30 degrees.

2. The determination of the Bowen ratio should be based on a simple un-weighted geometric mean (i.e., no direction or distance dependency) for a representative domain, with a default domain defined by a 10-km by 10-km region centered on the measurement site.
3. The determination of the albedo should be based on a simple un-weighted arithmetic mean (i.e., no direction or distance dependency) for the same representative domain as defined for Bowen ratio, with a default domain defined by a 10-km by 10-km region centered on the measurement site.

Sectors used to define the meteorological surface characteristics for the airport site as well as for a sensitivity study (discussed below) for the project site are shown in Figures 3-4 and 3-5.

Table 3-12 Meteorological Data Used in Running AERMET

Met Site	Latitude	Longitude	Base Elevation (m)	Data Source	Data Format
Dulles Airport, VA	38.934	-77.447	88	NCDC	CD-144
Sterling, VA	38.983	-77.467	85	WebMet	6201FB

Figure 3-3 Location of Project Site Relative to Dulles International Airport

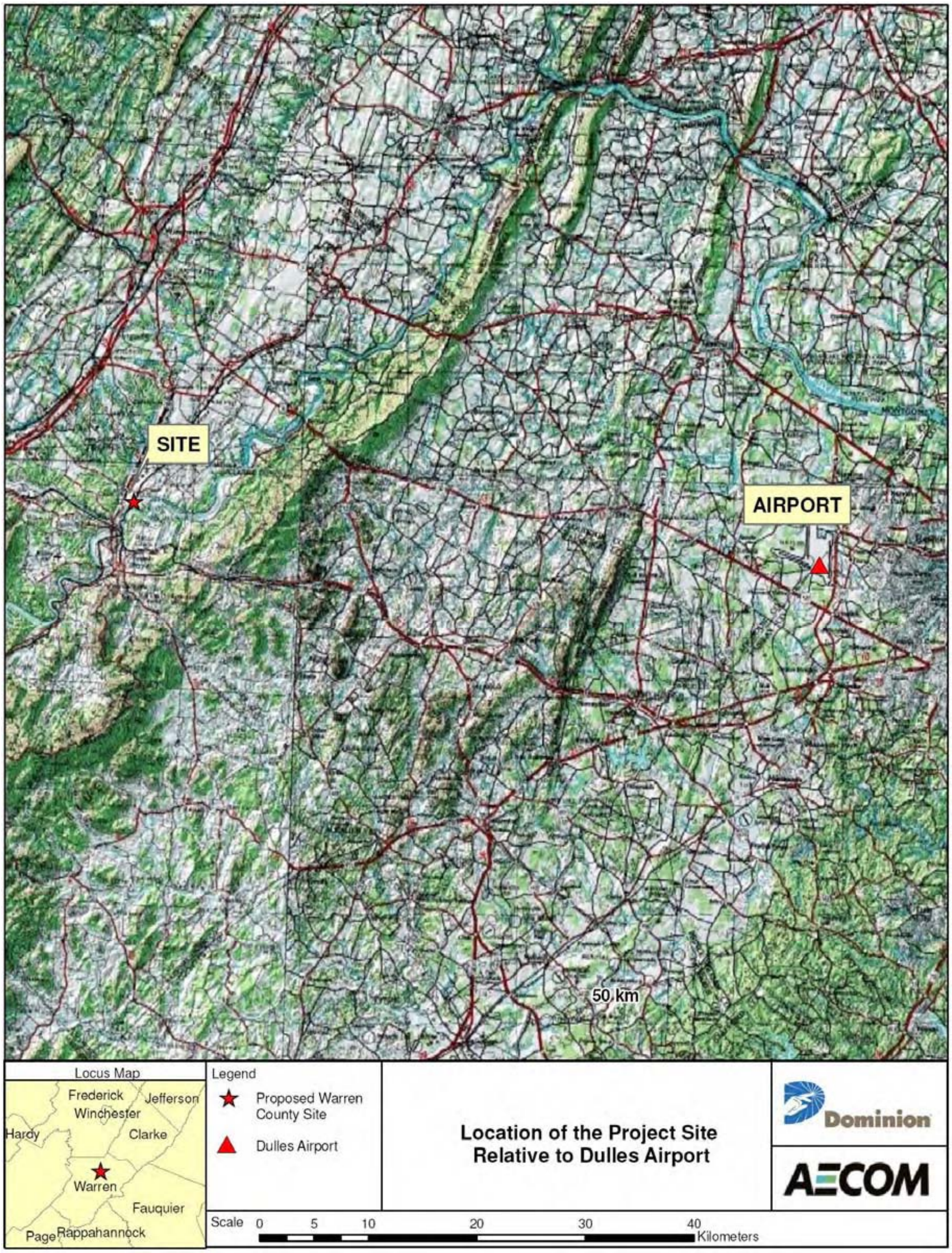


Figure 3-4 Sectors Used for Surface Characteristics at Dulles International Airport

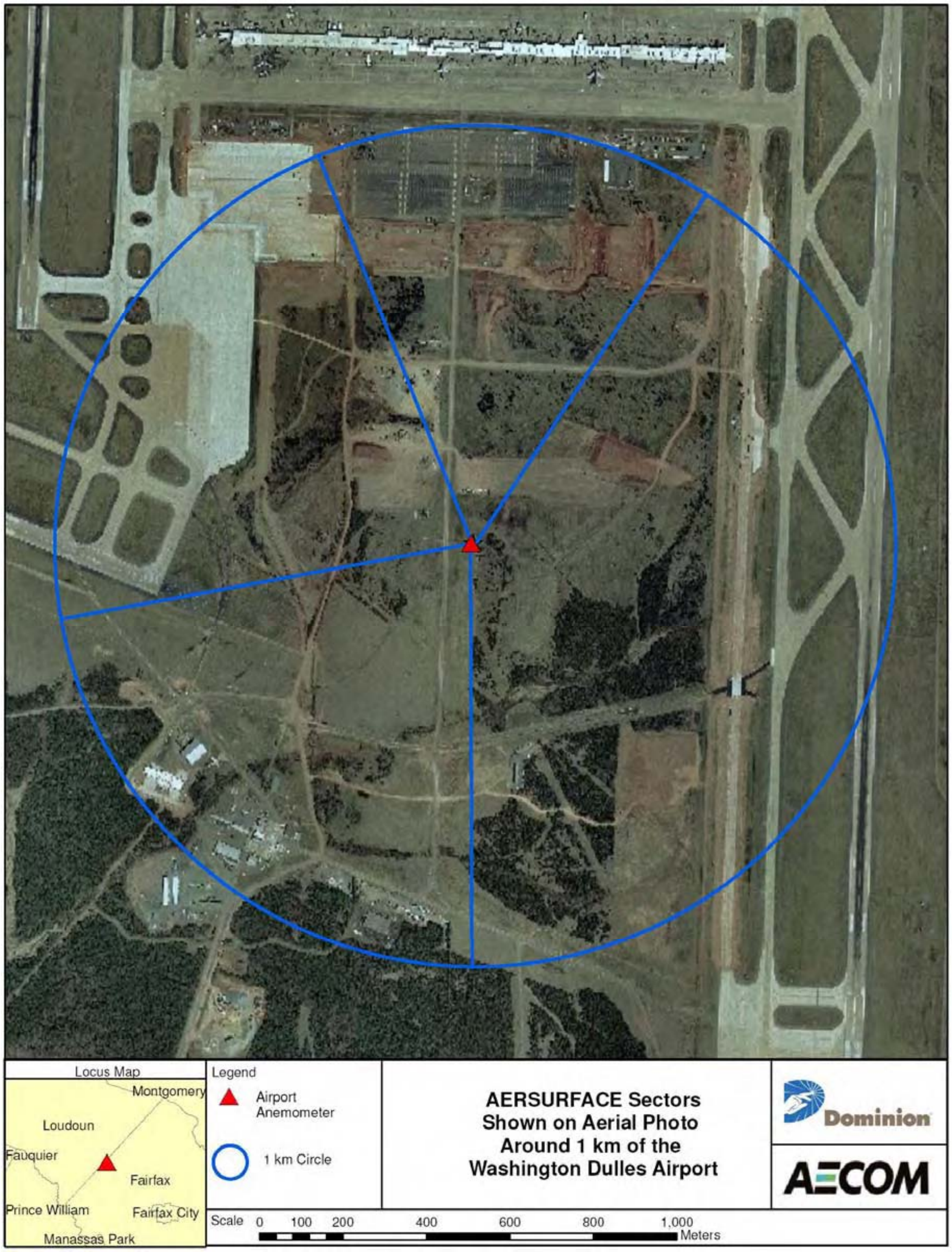
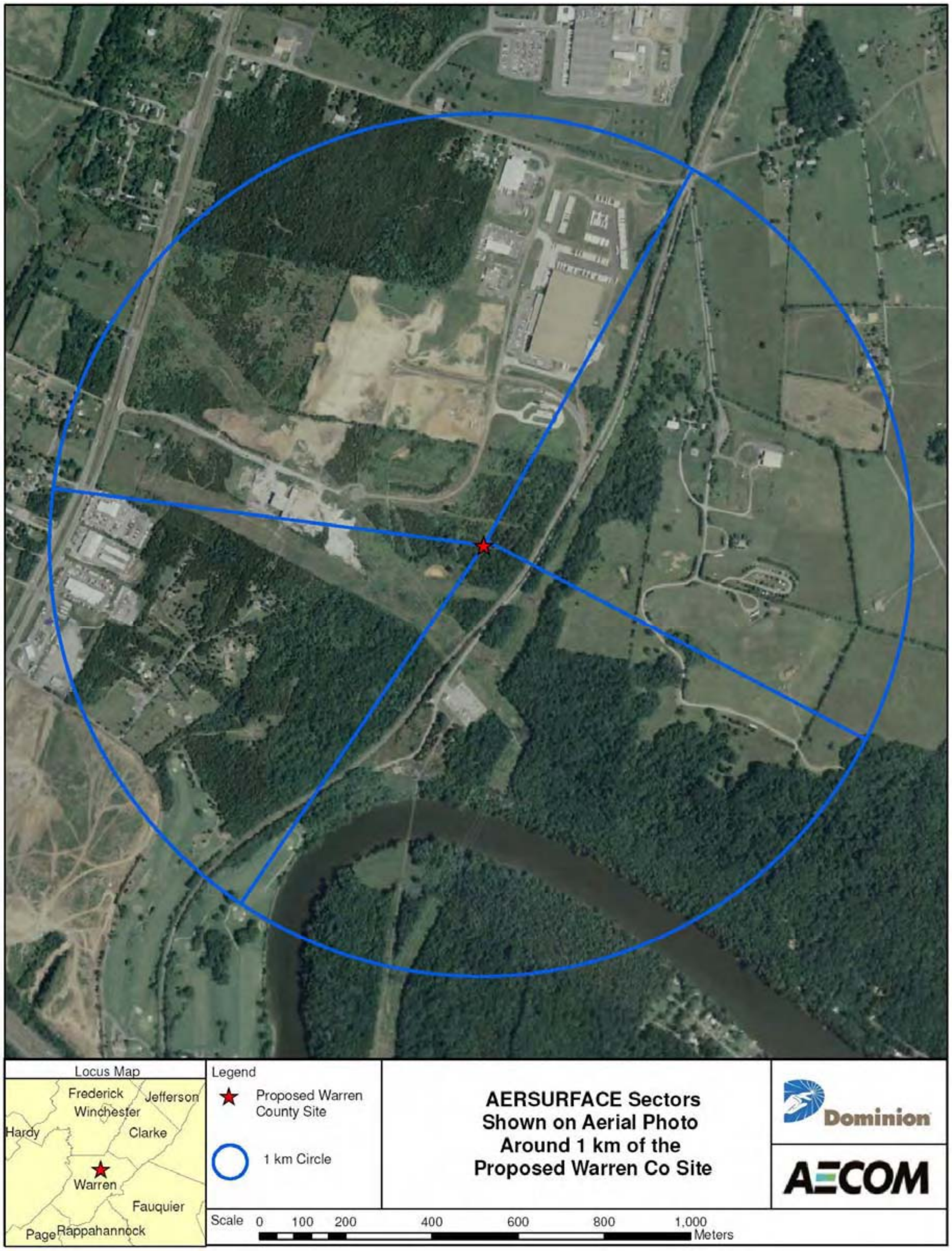


Figure 3-5 Sectors Used for Surface Characteristics at the Project Site



The AIG recommends that the surface characteristics be determined based on digitized land cover data. US EPA has developed a tool called AERSURFACE that can be used to determine the site characteristics based on digitized land cover data in accordance with the recommendations from the AIG discussed above. AERSURFACE incorporates look-up tables of representative surface characteristic values by land cover category and seasonal category. AERSURFACE, or an equivalent procedure, will be applied with the instructions provided in the AERSURFACE User's Guide.

The current version of AERSURFACE (Version 08009) supports the use of land cover data from the USGS National Land Cover Data 1992 archives[1] (NLCD92). The NLCD92 archive provides data at a spatial resolution of 30 meters based upon a 21-category classification scheme applied over the continental U.S. The AIG recommends that the surface characteristics be determined based on the land use surrounding the site where the surface meteorological data were collected. The selection of the land use types assigned in the NLCD92 database was reviewed and altered with justification provide in Appendix D based upon an analysis of the NLCD92 database.

As recommended in the AIG for surface roughness, the 1-km radius circular area centered at the meteorological station site can be divided into sectors for the analysis; each chosen sector has a mix of land uses that is different from that of other selected sectors. The sectors used for the airport and the project are shown in Figure 3-4 and 3-5 and also in Figures 3-6 and 3-7 for land use depiction.

In AERSURFACE, the various land cover categories are linked to a set of seasonal surface characteristics. As such, AERSURFACE requires specification of the seasonal category for each month of the year. The following five seasonal categories are supported by AERSURFACE, with the applicable months of the year specified for this site.

- Midsummer with lush vegetation (May-September).
- Autumn with un-harvested cropland (October-November).
- Late autumn after frost and harvest, or winter with no snow (December-February)
- Winter with continuous snow on ground (none).
- Transitional spring with partial green coverage or short annuals (March-April).

For Bowen ratio, the land use values are linked to three categories of surface moisture corresponding to average, wet and dry conditions. The surface moisture condition for the site may vary depending on the meteorological data period for which the surface characteristics will be applied. AERSURFACE applies the surface moisture condition for the entire data period. Therefore, if the surface moisture condition varies significantly across the data period, then AERSURFACE can be applied multiple times to account for those variations. As recommended in AERSURFACE User's Guide, the surface moisture condition for each month will be determined by comparing precipitation for the period of data to be processed to the 30-year climatological record, selecting "wet" conditions if precipitation is in the

[1] http://edcftp.cr.usgs.gov/pub/data/landcover/states/

upper 30th-percentile, “dry” conditions if precipitation is in the lower 30th-percentile, and “average” conditions if precipitation is in the middle 40th-percentile. The 30-year precipitation data set used in this modeling will be taken from Dulles International Airport, VA. Appendix E contains the 30-years of monthly precipitation data from the Southeast Regional Climate Center (SERCC). The 30-year period of record used to establish the 30-year average monthly precipitation totals include 1979 through 2008.

The monthly designations of surface moisture input to AERSURFACE are summarized in Table 3-13.

Table 3-14 presents a comparison of surface roughness length (Zo) between the two sites, using the NLCD 1992 data directly. Roughness length is a measure of the average roughness of a surface over which the air is flowing. The values in the table represent the average throughout the entire 360 degree circle. Values are presented for each month of the year. Of the three surface characteristics input to AERMOD (albedo, Bowen ratio and surface roughness length), EPA has determined (Brode et al., 2008) that AERMOD is likely to be most sensitive to surface roughness length.

An inspection of Table 3-14 indicates that the while the albedo and Bowen ratio values are comparable between the two sites, the surface roughness at the airport site is lower than at the project site due to the inherently smooth and cleared surfaces that characterize airports. However, the AIG states that “…a difference in *Zo* for one application may translate into an unacceptable difference in the design concentration, while for another application the same difference in Z*o* may lead to an insignificant difference in design concentration. If the reviewing agency is uncertain as to the representativeness of a meteorological measurement site, a site-specific sensitivity analysis may be needed in order to quantify, in terms of expected changes in the design concentration, the significance of the differences in each of the surface characteristics.” An additional consideration would be that if the use of the airport surface characteristics yields predicted results that are similar to or higher than those obtained using the project site surface characteristics, then the use of the airport data with airport surface characteristics should be acceptable for the permit application.

Table 3-13 AERSURFACE Bowen Ratio Condition Designations

Month	1988	1989	1990	1991	1992
January	Average	Average	Wet	Average	Average
February	Average	Average	Dry	Dry	Average
March	Dry	Average	Average	Wet	Average
April	Dry	Average	Wet	Dry	Average
May	Wet	Wet	Average	Dry	Average
June	Dry	Wet	Dry	Wet	Average
July	Wet	Wet	Wet	Average	Wet
August	Average	Dry	Wet	Dry	Dry
September	Dry	Average	Dry	Average	Wet
October	Dry	Wet	Wet	Dry	Average
November	Average	Average	Average	Average	Wet
December	Dry	Dry	Wet	Wet	Wet

Figure 3-6 1-km Radius for Dulles International Airport With Surface Roughness Sectors Shown on Land Use Imagery

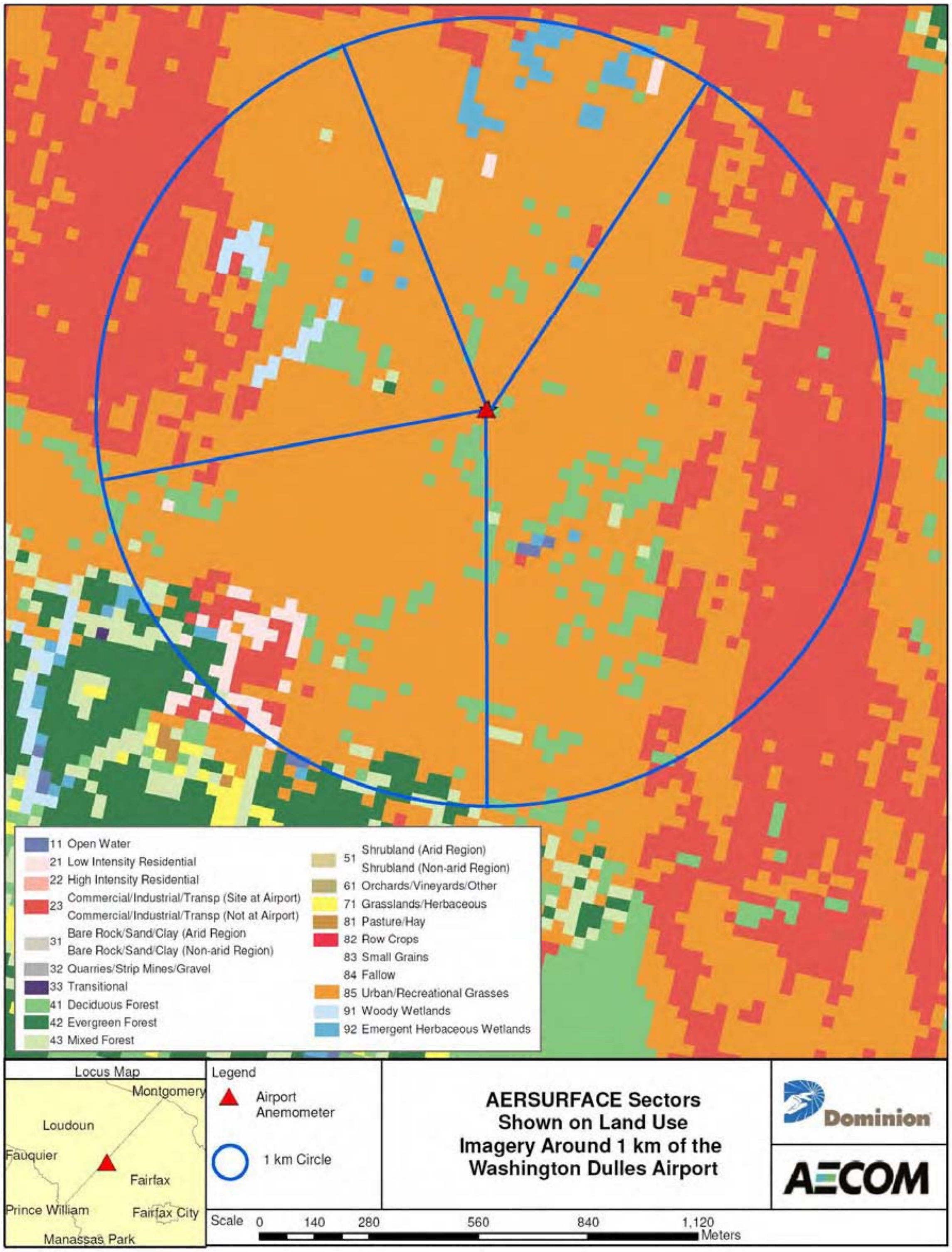


Figure 3-7 1- km Radius Circle for the Project Site with Surface Roughness Sectors Shown on Land Use Imagery

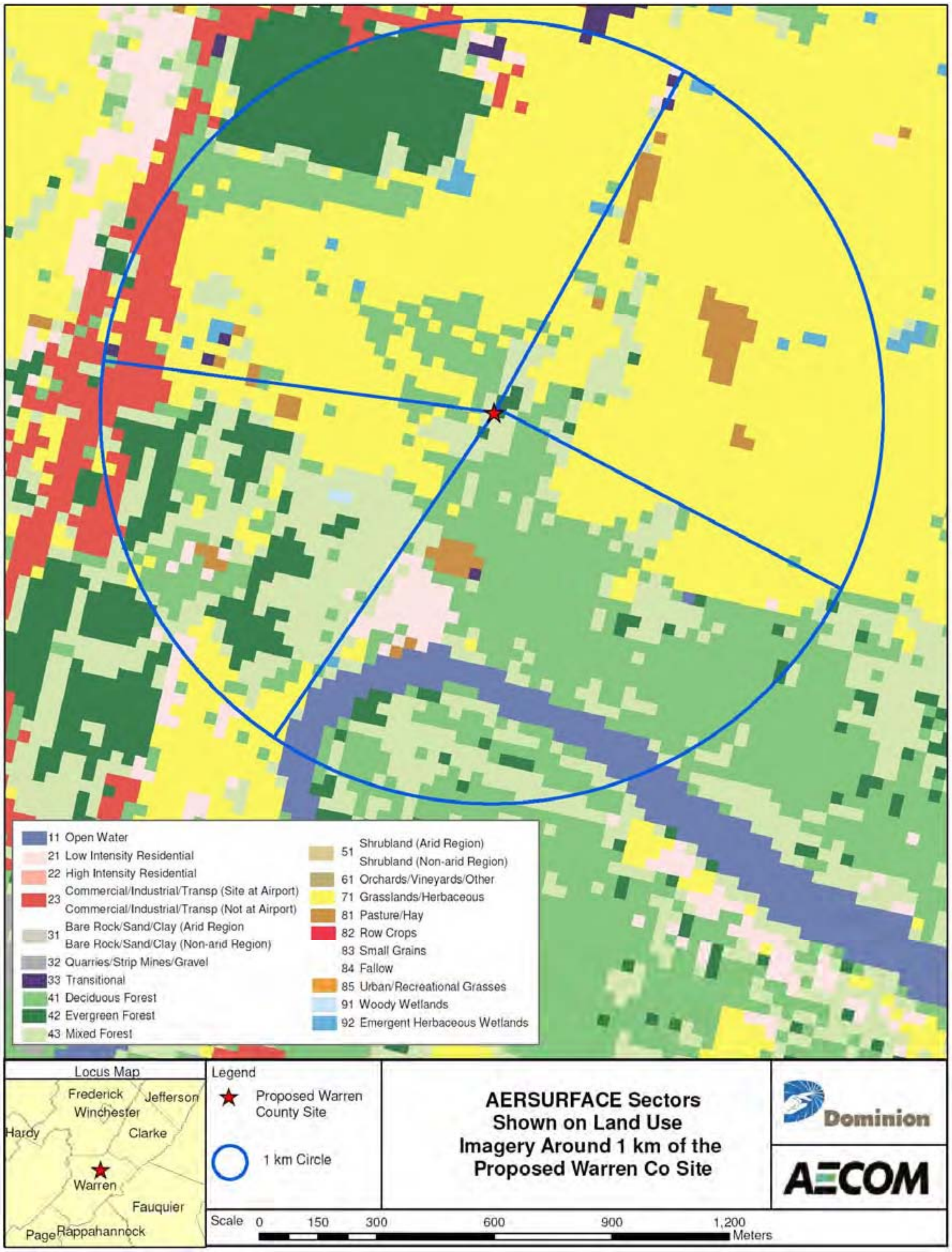


Table 3-14 Comparison of Surface Characteristics Between Dulles Airport and the Project Site

Month	Project Site Albedo	Project Site Bowen Ratio	Project Site Surface Zo	Airport Albedo	Airport Bowen Ratio	Airport Surface Zo
January	0.17	0.73	0.17	0.17	0.84	0.021
February	0.17	1.02	0.17	0.17	1.15	0.021
March	0.15	0.40	0.24	0.15	0.56	0.074
April	0.15	0.59	0.24	0.15	0.80	0.074
May	0.17	0.44	0.46	0.16	0.60	0.129
June	0.17	0.61	0.46	0.16	0.82	0.129
July	0.17	0.35	0.46	0.16	0.49	0.129
August	0.17	0.61	0.46	0.16	0.82	0.129
September	0.17	0.64	0.46	0.16	0.85	0.129
October	0.17	1.28	0.46	0.16	1.43	0.129
November	0.17	1.45	0.46	0.16	1.60	0.129
December	0.17	0.86	0.17	0.17	0.98	0.021

Albedo and surface roughness values represent the average throughout the entire 360 degree circle. Bowen ratio values represent the average throughout the entire 360 degree circle and average over 5 meteorological years. The selection of the land use types assigned in the NLCD92 database will be reviewed and may be altered with justification based upon a site-specific analysis.

As part of this protocol preparation, we conducted sensitivity AERMOD modeling runs for one of the turbine design layouts (the Siemens turbine) with the turbine modeled alone and also with all of the project sources of SO_2, NO_x, and particulate matter. This modeling was done with Dulles airport meteorological data, using site characteristics from both the airport and the project site.

The modeling results are shown in Table 3-15 for the turbine stacks only and for all sources in Table 3-16. The results for the turbine stacks only as well as all sources indicate that the use of the airport surface characteristics will provide comparable or higher impacts versus the use of the project site characteristics. Therefore, we propose to use the 1988-1992 Dulles International airport data with airport surface characteristics for this permit application.

Table 3-15 Sensitivity Modeling Results for Surface Characteristics Comparison: Turbine Stacks Only

Pollutant	Averaging Period	Rank	Airport Max Concentration (µg/m^3)	Site Max Concentration (µg/m^3)
Nitrogen Oxide	Annual	H	0.25	0.33
Carbon Monoxide	1-HR	H	31.34	21.42
Carbon Monoxide	8-HR	H	7.97	5.51
Particulate Matter (<10)	24-HR	H	4.47	3.55
Particulate Matter (<10)	Annual	H	0.19	0.27

Table 3-16 Sensitivity Modeling Results for Surface Characteristics Comparison: All Stacks

Pollutant	Averaging Period	Rank	Airport Max Concentration (µg/m^3)	Site Max Concentration (µg/m^3)
Nitrogen Oxide	Annual	H	0.61	0.64
Carbon Monoxide	1-HR	H	432.96	360.69
Carbon Monoxide	8-HR	H	31.27	26.42
Particulate Matter (<10)	24-HR	H	4.47	5.92
Particulate Matter (<10)	Annual	H	0.29	0.94

3.5 Good Engineering Practice Stack Height Analysis

A Good Engineering Practice (GEP) stack height analysis will be performed based on the proposed plant design to determine the potential for building-induced aerodynamic downwash for the proposed cooling towers and diesel generators stacks. The analysis procedures described in EPA's Guidelines for Determination of Good Engineering Practice Stack Height (EPA, 1985), Stack Height Regulations (40 CRF 51), and current Model Clearing house guidance will be used.

The GEP formula height is based on the observed phenomena of disturbed atmospheric flow in the immediate vicinity of a structure resulting in higher ground level concentrations at a closer proximity to the building than would otherwise occur. It identifies the minimum stack height at which significant aerodynamic downwash is avoided. The GEP formula stack height, as defined in the 1985 final regulations, is calculated from:

$H_{GEP} = H_{BLDG} + 1.5L$

Where:

- H_{GEP} is the maximum GEP stack height
- H_{BLDG} is the height of the nearby structure, and
- L is the lesser dimension (height or projected width) of the nearby structure

Both the height and width of the structure are determined from the frontal area of the structure projected onto a plane perpendicular to the direction of the wind. In all instance, the GEP stack height is based on the plane projections of any nearby building which result in the greatest justifiable height. For purposes of the GEP analysis, nearby refers to the "sphere of influence", defined as five times the height or width of the building, whichever is less, downwind from the trailing edge of the structure. In the case where a stack is not influenced by nearby structures, the maximum GEP stack height is defined as 65 meters.

The EPA's Building Profile Input Program (BPIP-Version 04274) version that is appropriate for use with PRIME algorithms in AERMOD will be used to incorporate downwash effects in the model. The building dimensions of each structure will be input in BPIPPRM program to determine direction specific building data. PRIME addresses the entire structure of the wake, from the cavity immediately downwind of the building, to the far wake.

3.6 Receptor Grid and AERMAP Processing

3.6.1 Class I Receptor Grid

The nearest Class I Area, Shenandoah National Park, is located approximately 7 km south of the Warren County Project site. Because of the proximity of the Class I Area to the proposed site, AERMOD will be used to access the impacts from the facility on Shenandoah National Park. In addition to the National Park Services' receptor grid for Shenandoah National Park, the Class I grid will consist of strategically spaced receptors within the Park. The grid will consist of receptors spaced at 100 m out to 10 km from the project site, 500 m between 10 and 30 km from the project site, and 1000 m spacing between 30 and 50 km from the project site. The receptor grid used in the modeling analysis will be based on NAD 83 datum and in zone 17.

3.6.2 Class II Receptor Grid

The Class II grid will consist of receptors spaced 25 m apart along the fence line. A spacing of 50 m will be used for the receptors beyond the fence line and extending out to 1 km from the fence line. Beyond 1 km from the fence line, a spacing of 100 m will be used up to 2.5 km from the plant. Between 2.5 and 5 km, a spacing of 500 m will be used. Between 5 and 10 km, a spacing of 1000 m will be used. Beyond 10 km, a spacing of 2000 m will be used. No receptors within the Shenandoah National Park will be included in the Class II analysis. Receptors with 1000-m spacing will be placed at the boundary of the Class I Area extending out to 20 km. The receptor grid used in the modeling analysis will be based on NAD 83 datum and in zone 17.

The extent of this grid is expected to be sufficient to capture maximum impacts in the Class II area. However, if highest impacts are predicted at the edge of the grid at a distance of 20 km from the project site, additional receptors may be required to ensure that the distance covered by the SIA is determined. Furthermore, for those pollutants and averaging periods that are modeled to be insignificant and whose impacts are predicted outside 50-m spaced receptors in the Class II area, a refined receptor grid (50-m spacing) will be used to ensure the maximum impacts are resolved. For those pollutants and averaging periods that are modeled to have significant impacts, 50-m spaced receptors will be used to resolve the highest concentrations as a part of the SIA determination. Cumulative NAAQS and Increment modeling will be limited to those receptors for which the SILs are exceeded for modeling of the project impacts alone.

3.6.3 AERMAP Processing

The AERMAP (version 09040) processor program will be used to calculate terrain elevations and critical hill heights for the Class I and Class II receptor grids (NAD83 datum and zone 17) using National Elevation Data (NED). The dataset that will be downloaded from the USGS website (http://seamless.usgs.gov/) will consist of 1/3 arc second (~10 m resolution) NED. As per the AERMAP User's Guide (USEPA, 2004), the domain will be sufficient to ensure that all significant nodes are included such that all terrain features that exceed a 10% elevation slope from any given receptor are considered.

3.7 Class II Area Modeling Analyses

A refined modeling analysis will be conducted using AERMOD (version 09292). The analysis will be conducted to demonstrate compliance with both state and federal applicable ambient air quality standards. For those pollutants and averaging periods that predict impacts above their applicable SIL, as shown in Table 3-1, a refined cumulative modeling analysis which will consider additional NAAQS and PSD sources will be conducted to determine compliance with the NAAQS and PSD increments for those pollutants modeled to have significant impacts.

3.7.1 Class II Area SIL Analysis

The Class II Area SIL analysis will be conducted using the five years of meteorological data prepared as described in Section 3.4. This modeling analysis will be used to make a determination of significance for PM_{10}, NO_2 and CO. For those pollutants and averaging periods with significant impacts, the significant impact area (SIA) will be determined from all possible operating scenarios, and then the air quality analysis will then be expanded to include a demonstration of compliance with applicable ambient standards and PSD increments as described in Section 3.7.2.

3.7.2 Compliance with Class II Area Ambient Air Quality Standards and PSD Increments

As stated previously for those pollutants and averaging periods determined to be less than the SILs, no further analysis will be performed. The discussion below applies only to those pollutants and averaging periods for which a significant impact is predicted with AERMOD.

Compliance with the PSD Increments and NAAQS would be based on the sum of the following:

- Modeled impacts attributable to the project.
- Modeled impacts from “nearby” sources.
- Representative ambient background concentration (NAAQS only).

Impacts attributable to project and “nearby” sources will be estimated using AERMOD.

An inventory of sources will be obtained from the appropriate state agencies for each pollutant which exceeds the SIL, covering facilities within 50 km plus the SIA distance that could contribute significantly to ambient concentrations within the SIL radius. Two classes of facilities will be included. For the evaluation of PSD increments, only sources that received PSD permits or have been designated by the appropriate state agency as PSD increment consuming sources will be included. Also, any sources that expand PSD increment could be included in the analysis. For the evaluation of NAAQS, all sources of the applicable pollutant will be included. Section 4 provides more detail on the representative monitored ambient background data and the processing of the nearby source inventory. However, in case of a missing PSD inventory from the State/Agency, a conservative approach will be followed. All the nearby sources that would be modeled as NAAQS sources will be considered to be PSD increment-consuming sources.

For the cumulative impact analysis, the high 2nd high short-term and high annual impacts from the proposed project, as well as influencing nearby emission sources, will be compared with the NAAQS and PSD increments. The standards are presented in Table 3-17 and 3-18. For the NAAQS analysis, a conservative background concentration will be added to the high 2nd high short-term and high annual impacts to determine compliance.

Table 3-17 Ambient Air Quality Standards

Pollutant	Averaging Period[2]	National AAQS[1]	
		Primary	Secondary
Carbon Monoxide	8-hour	10,000	--[3]
	1-hour	40,000	--[3]
Nitrogen Dioxide	Annual	100	100
PM-2.5	Annual	15	15
	24-hour	35	35
PM-10	24-hour	150	150

All standards in this table are expressed in $\mu g/m^3$.

Short term ambient standards may be exceeded once per year; annual standards may never be exceeded.

Source: 9 VAC 5 Chapter 30

Table 3-18 PSD Increments

Pollutant and Averaging Period	Class II Increment ($\mu g/m^3$)
Nitrogen Dioxide	
Annual Arithmetic Average	25
Particulate Matter (PM-10)	
Annual Geometric Average	17
24-Hour	30

Source: 9 VAC 5-80-1635

3.8 Class I Area Modeling Analyses

Sections 3.6.1 and 3.4 discuss the modeling approach (AERMOD for receptors out to 50 km for Shenandoah National Park only) and the meteorological data (Dulles 1988-1992) data to be used for modeling NAAQS compliance, PSD increments (for SO_2, NO_2, and PM_{10}), and acidic deposition. For visual plume impacts for 5 defined viewpoints within Shenandoah National Park, PLUVUE II will be used with the 1988-1992 Dulles meteorological data, following procedures used in previous permitting for CPV at this project site.

Modeling procedures for the $PM_{2.5}$ NAAQS compliance analysis are discussed in Section 5.5.

3.8.1 Class I Area SIL Analysis

For compliance with the NAAQS and PSD increments, the first step in the modeling analysis is to model the proposed project emissions to determine whether the peak impacts exceed the applicable SILs. The proposed Class I SILs are provided in Table 3-19, based upon proposed values in a July 23, 1996 Federal Register notice for SO_2, NO_2, and PM_{10}, and upon proposed values in a September 21, 2007 Federal Register notice for $PM_{2.5}$.

For the NO_2 SIL (as well as for the analysis of NAAQS compliance and PSD increments), we will first use the Tier 1 approach discussed in Section 5.2.4 of 40 CFR Part 51 Appendix W (EPA modeling guidelines), first assuming 100% conversion of NO_x to NO_2. We will use the Tier 2 approach of a 75% conversion of NO_x to NO_2 , or Tier 3 using the Ozone Limiting Method or the Plume Volume Molar Ratio Method if needed. Hourly ozone data from the Shenandoah Big Meadows CASTNET site (concurrent with the AERMOD meteorological data) would be used if a Tier 3 approach is used. This use of a Tier 2 or Tier 3 approach for determining a significant impact as well as NAAQS compliance and PSD increments is specified as an EPA-approved procedure in Section 10.2.1c of Appendix W:

“If the concentration estimates from screening techniques indicate a significant impact or that the PSD increment or NAAQS may be approached or exceeded, then a more refined modeling analysis is appropriate and the model user should select a model according to recommendations in Sections 4–8.”

Table 3-19 Proposed SILs for Class I Modeling

Pollutant	3-hour ($\mu g/m^3$)	24–hour ($\mu g/m^3$)	Annual ($\mu g/m^3$)
PM_{10}	NA	0.3	0.16
NO_2	NA	NA	0.10
$PM_{2.5}$	NA	0.07	0.06

NA = not applicable

3.8.2 Compliance with Class I Area Ambient Air Quality Standards and PSD Increments

If the modeled project impacts exceed the Class I SILs for any of the pollutants listed above, then a cumulative modeling analysis will be necessary for that pollutant. The proposed analysis for $PM_{2.5}$ has already been described in Section 5.5. In a procedure similar to the Tier 1 approach for $PM_{2.5}$, we will determine a representative monitored background for the pollutant of concern and also model nearby sources that are likely to cause a significant concentration gradient in the vicinity of the proposed source. Cumulative modeling will be done only for those receptors that exceed the applicable SIL. The SIA will be defined as the furthest distance from the source for any receptor that exceeds the SIL. The nearby source inventory is discussed in Section 4.0.

The applicable PSD increments for Class I areas are listed in Table 3-20.

Table 3-20 Applicable PSD Class I Increments

Averaging Period/ Pollutant	Class I PSD Increment [a]
Annual NO_2	2.5
24-hour PM_{10}	8
Annual PM_{10}	4
Source: 9 VAC 5-80-1635	

[a] Highest value used for annual averages; second-highest for the 24-hour average

4.0 Background Air Quality

4.1 Available Representative Data

Ambient air quality data are used to represent the contribution to total ambient air pollutant concentrations from non-modeled sources. Representative ambient air quality background concentrations for the proposed facility in Warren County, Virginia will be proposed to VA DEQ based on guidance from the agency.

4.2 Pre-construction Monitoring Waiver Request

The PSD regulations require that a PSD permit application contain an analysis of existing air quality for all regulated pollutants that the source has the potential to emit in significant amounts. The definition of existing air quality can be satisfied by air measurements from either a state-operated or private network, or by a pre-construction monitoring program that is specifically designed to collect data in the vicinity of the proposed source. A source may request an exemption from the pre-construction monitoring program if the ambient impacts from the source are less than the de minimis levels established by the EPA or if existing data are representative of the air quality in the site vicinity.

It is requested that a source-specific pre-construction monitoring program not be required for the proposed Warren County Project. This will be supported by the existence of representative air quality data to be provided by VA DEQ as discussed in Section 4.1. Dominion therefore requests written confirmation that a pre-construction monitoring program is not required.

In addition, it is also requested that a source-specific post-construction monitoring program not be required for the proposed Warren County Project. This will be supported by showing that emissions from the proposed project will not adversely impact any air quality. In addition, the existing VA DEQ operated monitoring network will collect data representative of post-construction air quality.

4.3 Nearby Source Inventory

Two levels of refinement will be applied to determine the list of sources to be explicitly modeled in the Class I and Class II cumulative NAAQS and PSD Increment impact assessments.

4.3.1 Initial Screening – Class I Area and Class II Area

For the initial screening, a summary will be generated of nearby sources that emit pollutants for which the Warren facility modeled above the SIL that are within a 50-km plus SIA radius of the proposed project. These sources will be obtained from the VA DEQ and other appropriate state or local agencies. Allowable emission rates for the facilities within a 50-km plus SIA radius are needed. All the sources which are located outside of 50 km plus the SIA distance will be eliminated from further modeling consideration.

4.3.2 Refinement of Emission Data and Permit File Review

Out of those facilities that are within the 50km plus the SIA distance, additional refinements will be applied. First, any facility with emissions less than 5 TPY (generally considered an insignificant source) will be excluded from the analysis because those impacts will be accounted for in the conservative monitoring background value.

Next, the remaining sources will be refined based on the Q/D ratio for each of the pollutants exceeding SILs. Sources will be screened based on a ratio of their short-term emissions (for all facility stacks combined) expressed in tons per year (Q) divided by the distance from the project site in kilometers (D). Sources with a Q/D ratio of less than 0.80 for SO_2 and NO_2, and 0.30 for PM_{10} will be presumed to cause an insignificant concentration gradient in the SIA modeling area. The Q/D thresholds are derived from the significant emissions increase for a proposed project (e.g., 40 tons per year for NO_X) divided by 50 km. Finally, any source identified as a fugitive source located 10 km beyond the SIA will be eliminated.

Because there are expected to be data gaps in some of the emissions inventory records, a conservative approach will be followed as described below:

- Any missing stack parameters in the inventories will be filled with the 2005 NEI database.
- For the sources/facilities that cannot be found in 2005 NEI database, missing stack parameters will be filled with appropriate stack parameters to represent a worst-case modeling scenario - 10 ft for the stack height, 68°F for the stack exit temperature, 0.0003 fps for the stack exit velocity and 0.003 ft for the stack diameter

4.3.3 PSD Source Inventory

For the pollutants required to undergo a cumulative PSD increment analysis, all sources modeled as part of the NAAQS cumulative impact assessment will initially be considered PSD increment consuming sources. If the proposed project can demonstrate compliance with the Class I and Class II PSD increments using this conservative approach, then no additional modeling will be performed. However, if the modeled impacts exceed the applicable PSD increments, then additional modeling will be conducting only for the PSD increment-affecting sources (either consuming or expanding). In this instance, VA DEQ and the appropriate state agencies will be contacted to further investigate the NAAQS inventory to define those sources that are PSD increment-affecting sources.

5.0 Additional Impact Analysis

In accordance with 9 VAC 5-80-1755, additional impacts must be addressed for projects subject to PSD review. The various components of the additional impact analyses are discussed below.

5.1 Class I Area Air Quality Related Values

The AQRV analyses for Shenandoah National Park involve visibility and acidic deposition impacts. The applicable modeling approaches have been discussed in Section 3.2.

5.2 Visibility Analysis

As previously stated for plume visibility impacts inside Shenandoah National Park within 50 km, the PLUVUE II model will be used, consistent with past permitting on this project. The procedures for this analysis have been established and agreed to by the National Park Service for the previous permitting of the CPV project at the same site (see TRC Class I modeling report, 2003).

Following the procedures done in the past, the modeling approach consists of the elements described below.

- Five years of meteorological data (1988-1992) from Dulles airport will be used for the analysis, as discussed below.
- The 2003 TRC report refers to preliminary analyses that were conducted to identify a subset of conditions and hours for the PLUVUE II analysis. Details provided in Appendix E of that document describe specific wind directions of interest and consideration of views within the Park itself. This analysis reviewed the PLUVUE results from "typical average" conditions within possible meteorological combinations in order to eliminate most cases for which the plume contrast (|C|) and plume perceptibility (ΔE) results would be less than 85% of the Class I Levels of Concern for PLUVUE II (an absolute value of at least 0.017 for |C| and 0.85 for ΔE). This analysis will be repeated for this project due to the higher emissions relative to past permitting for CPV. Groups of hours for which the PLUVUE II results for "typical average" conditions exceed these reduced thresholds will be modeled individually for each applicable hour of meteorological conditions.
- Specific viewpoints discussed below have been selected for the plume visibility analysis. For each of these viewpoints, the meteorological data have been screened for the frequency of the occurrence of appropriate conditions during daylight hours and cases for which the plume was transported close to the observer (within 10 degrees). The final database includes only hours with non-overcast conditions because the PLUVUE II model assumes clear skies.
- Emissions rates for SO_2, NO_x, and PM_{10} are consistent with those being modeled for criteria pollutant concentrations. Although PLUVUE II double-counts the sulfur atoms in SO_2 and sulfate emissions, the small level of emissions in this case do not warrant an adjustment to PLUVUE II for this input.
- The PM_{10} emission rate includes both filterable and condensable components, including sulfates.

For the previous permitting, the National Park Service and VA DEQ agreed upon five viewpoints to be analyzed for plume visibility effects (see Figure 5-1, copied from the 2003 TRC report referenced above). Three of the selected locations are overlooks situated along Skyline Drive. These areas are directly accessible by automobile, have clear views of terrain, and are relatively unobstructed. Two other viewpoints were added by NPS staff. The viewpoints to be analyzed are described below, and are displayed in Figures 5-2 through 5-6 (copied from the 2003 TRC report).

- Shenandoah Valley Overlook: located about 9 km from the proposed project site, it offers views to the north toward Front Royal.
- Dickey Ridge: located about 11 km from the proposed project site, it offers views to the northeast within the Park, and views to the southeast and southwest toward terrain within the Park.
- Signal Knob Overlook: located about 12.5 km from the proposed project site, it offers fairly long views to the south, southwest, and southeast within Park boundaries. In addition, there is a view toward the west to areas beyond Park boundaries.
- Compton Gap Road: selected as a supplemental viewpoint by the NPS due to its location at the highest point along Compton Gap Road, about 14.6 km from the project site. It offers long views of Park terrain toward the southwest, and shorter views toward the west and northwest.
- Lands Run Road Gate: selected as a supplemental viewpoint by the NPS for its location where Lands Run Road crosses the western boundary of the Park. It is approximately 16.5 km from the proposed project site and it offers long views to the south and southwest, although viewing distances to the east are limited by elevated terrain.

PLUVUE II will be run for each hour identified from the 5-year meteorological period discussed above for meteorological conditions associated with the Class I Levels of Concern (an absolute value of at least 0.02 for |C| and 1.0 for ΔE). The 2003 analysis indicated 67 hours that exceeded the FLM FLAG 2000 PLUVUE significant impact levels noted above in the 2003 analysis, so these hours will likely be included in the new analysis. The results of the PLUVUE II analyses will be summarized by viewpoint, and the probability of potential future occurrences during peak project emission periods will be calculated by reviewing the frequency of hours determined to be above perceptible visibility thresholds, especially during periods of peak park visitation. Note that the threshold values specified above are considerably more stringent than the values of 0.05 for |C| and 2.0 for ΔE used for the Level 1 and 2 plume visibility modeling. For informational purposes, the frequency of hours above the Level 1 and 2 thresholds may also be presented.

The PLUVUE II predictions for |C| and ΔE will be compared to the Class I Levels of Concern as noted above. In addition, we may present as supplemental information the results of refinements to these threshold values that properly account for effects on perceptibility due to the apparent plume width. As noted by Richards et al. (2007; see Appendix B),

> "In the real world, plumes are viewed against a background of sky or terrain that does not have a uniform luminance and color, even when there are no clouds. For faint plumes, the effect of a plume is to introduce a small distortion in the luminance and color profile of the background. As the angle subtended by a plume increases (i.e., the plume fills a larger portion of the observers total field of view), the plume is spread over a larger change in the luminance and color of the background sky. For a given value of the plume contrast or color difference, the changes in luminance and color attributable to the plume become a smaller fraction of the naturally occurring variations in the luminance and color of the background sky. Thus, it is reasonable to believe that the adjustment needed to convert laboratory contrast thresholds into thresholds appropriate for the real world increases as the plume subtended angle increases."

The procedures for implementing an adjustment to |C| and ΔE are described by Richards et al. (2007) as well as Zell et al. (2007; see Appendix C). These procedures will be used to supplement the results obtained using the default threshold values for |C| and ΔE.

Figure 5-1 Scenic Overlooks Analyzed in PLUVUE II Plume Visibility Analysis

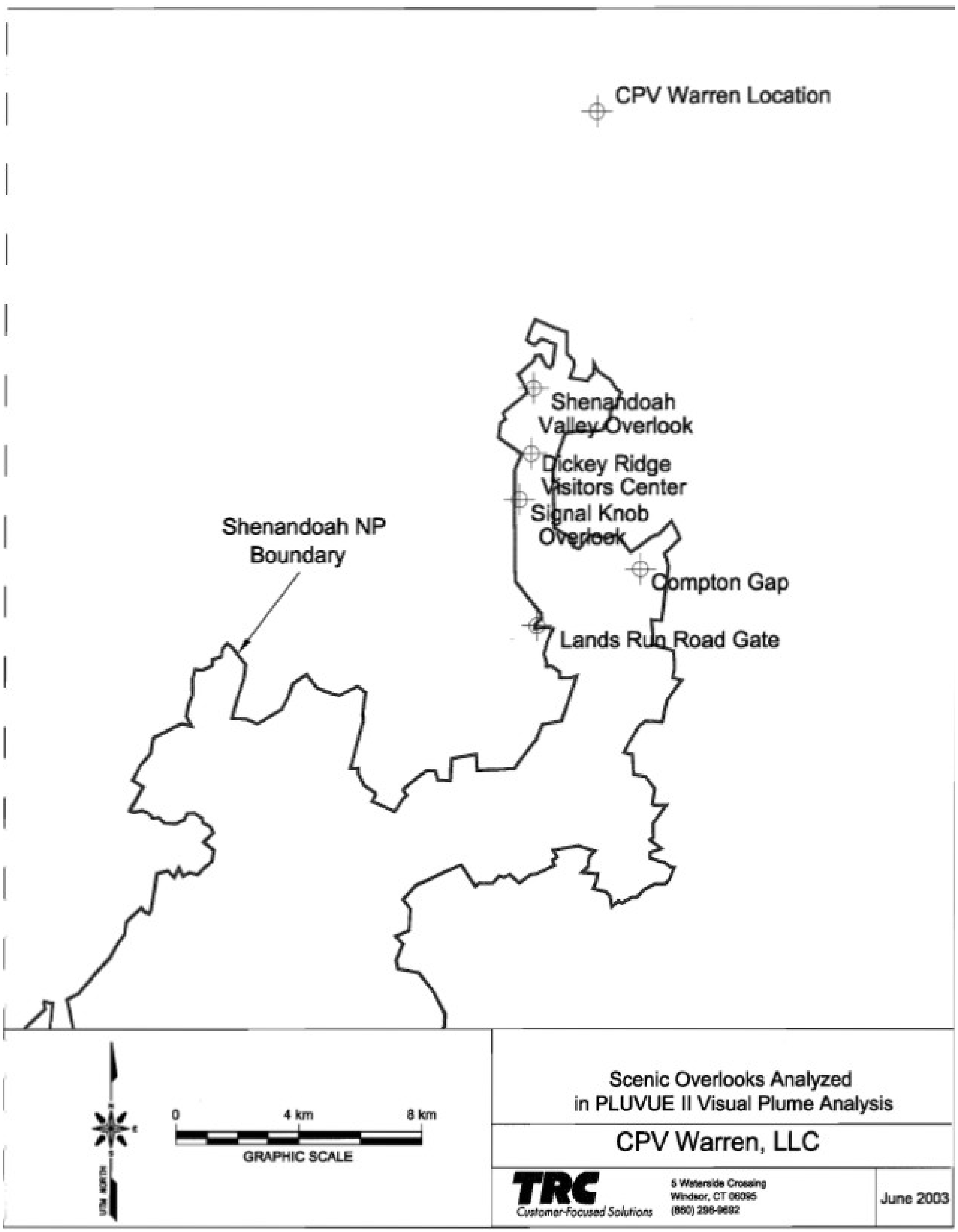


Figure 5-2 Lines of Sight for Shenandoah Valley Overlook

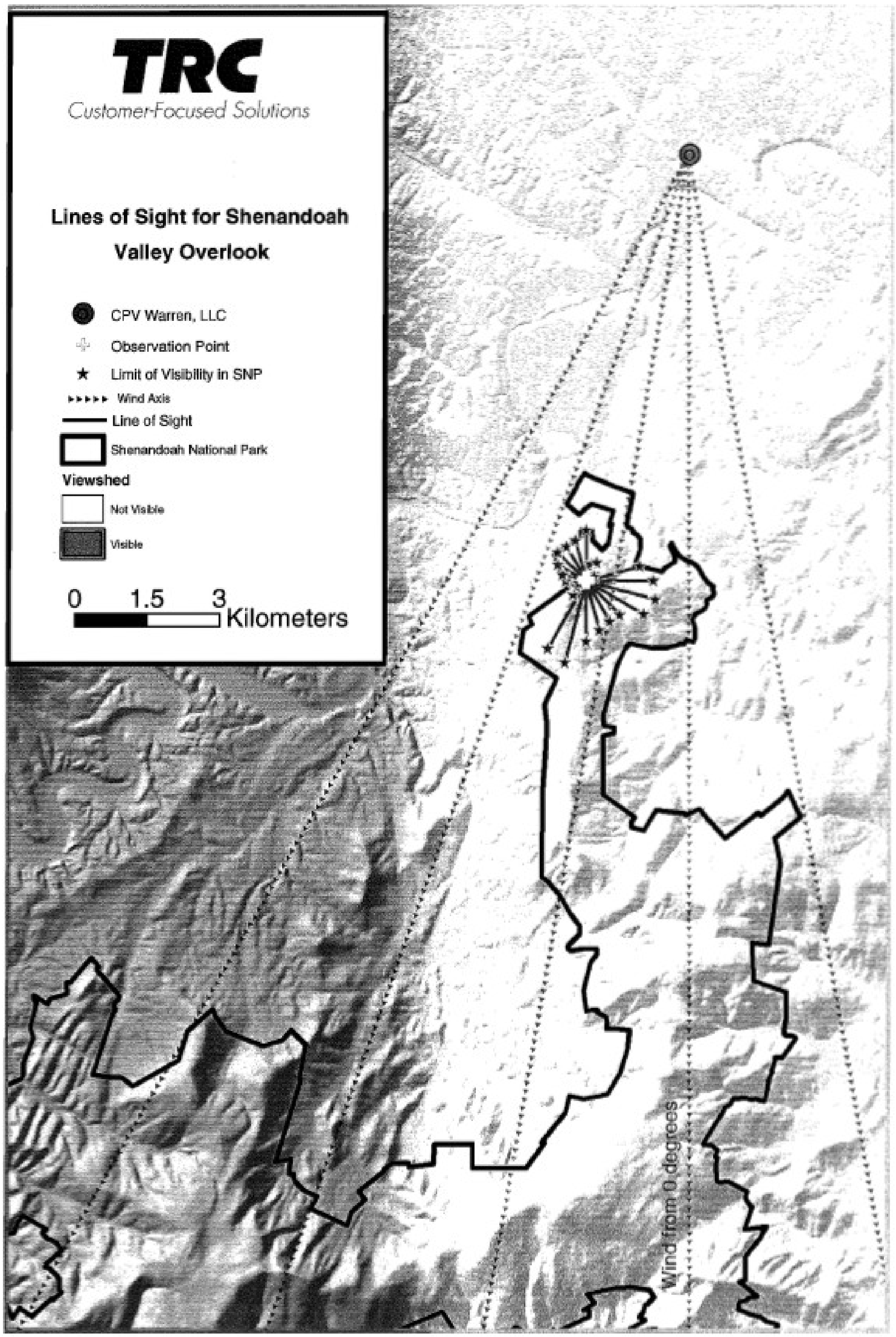


Figure 5-3 Lines of Sight for Dickey Ridge Visitor Center

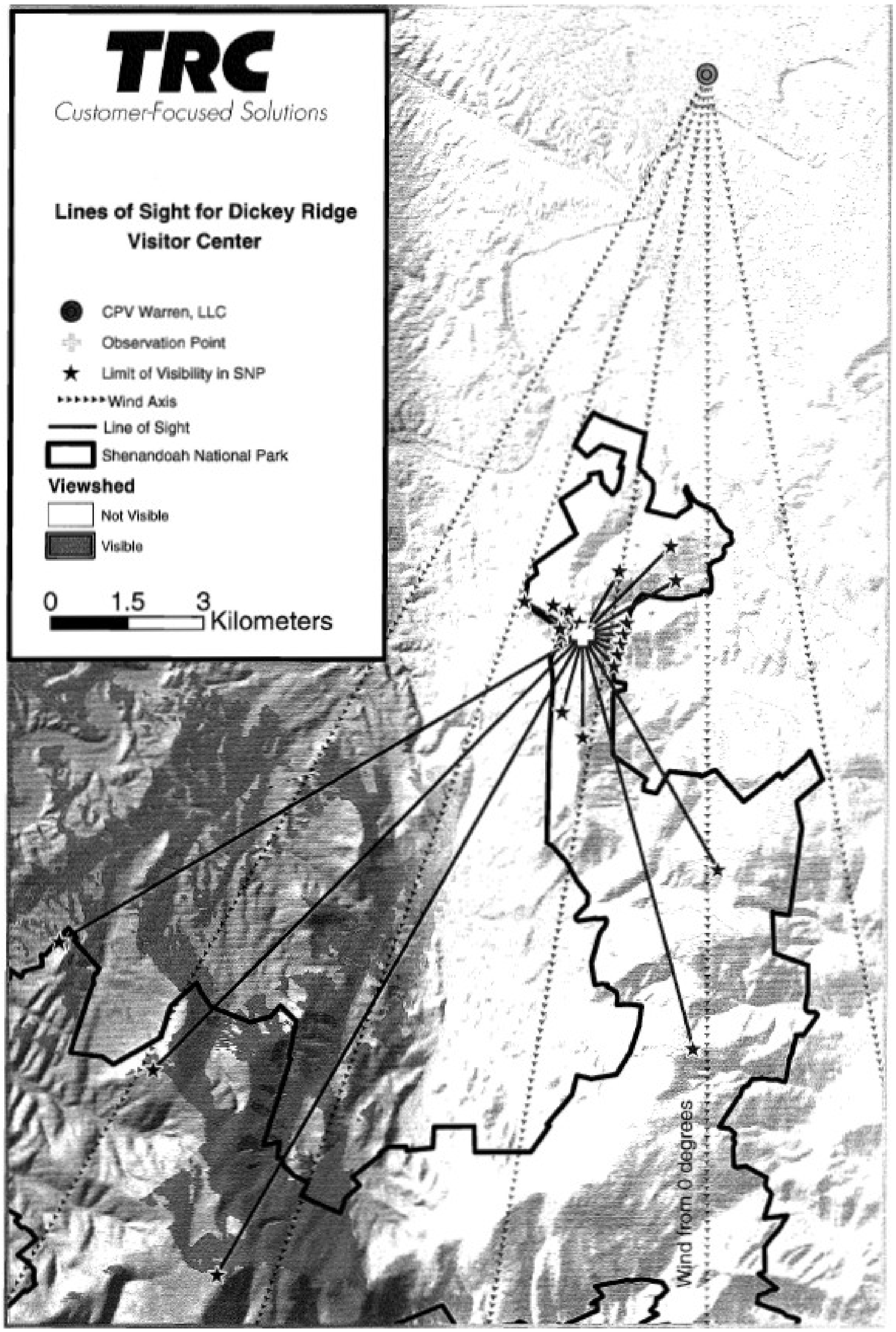


Figure 5-4 Lines of Sight for Signal Knob

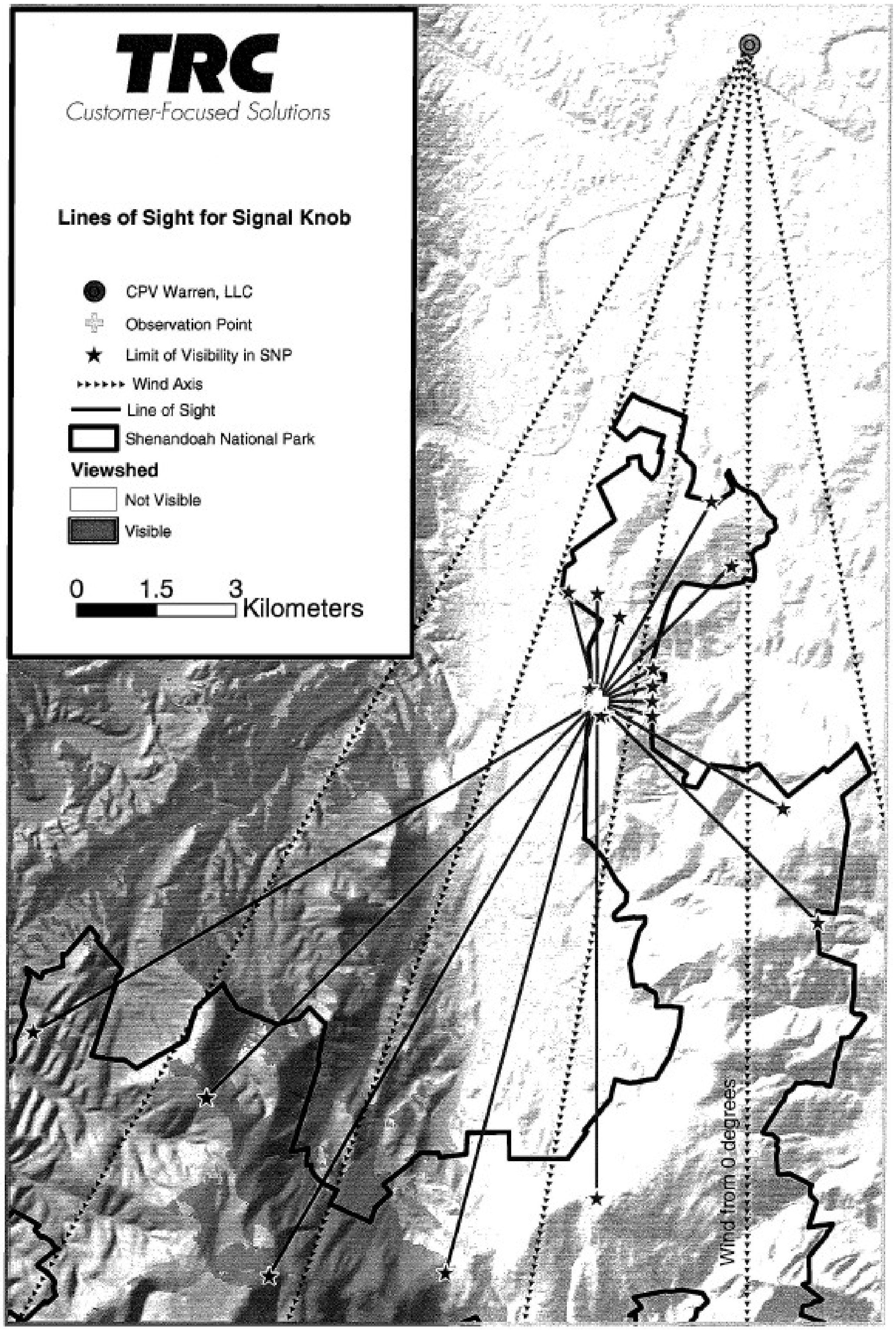


Figure 5-5 Lines of Sight for Compton Gap

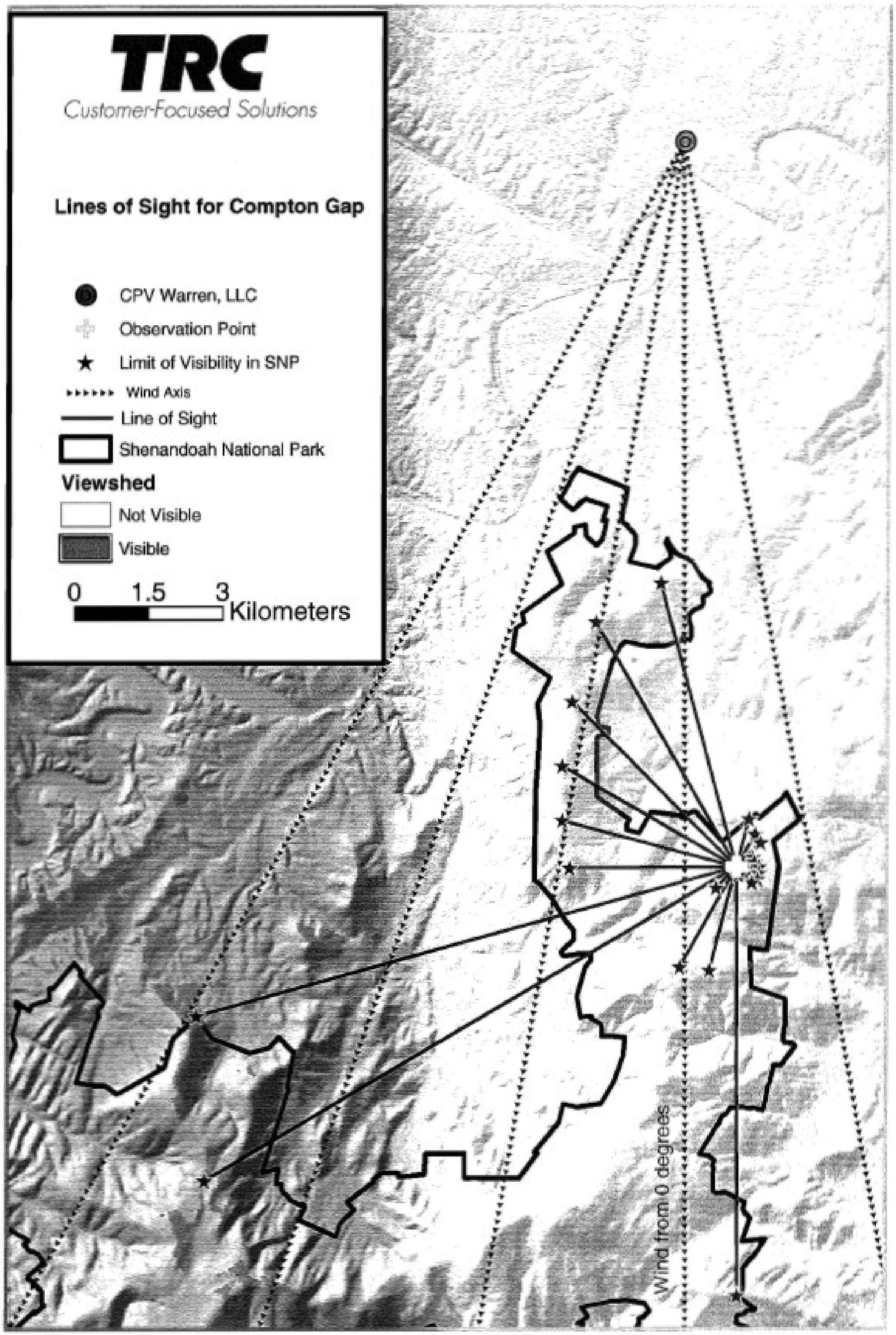
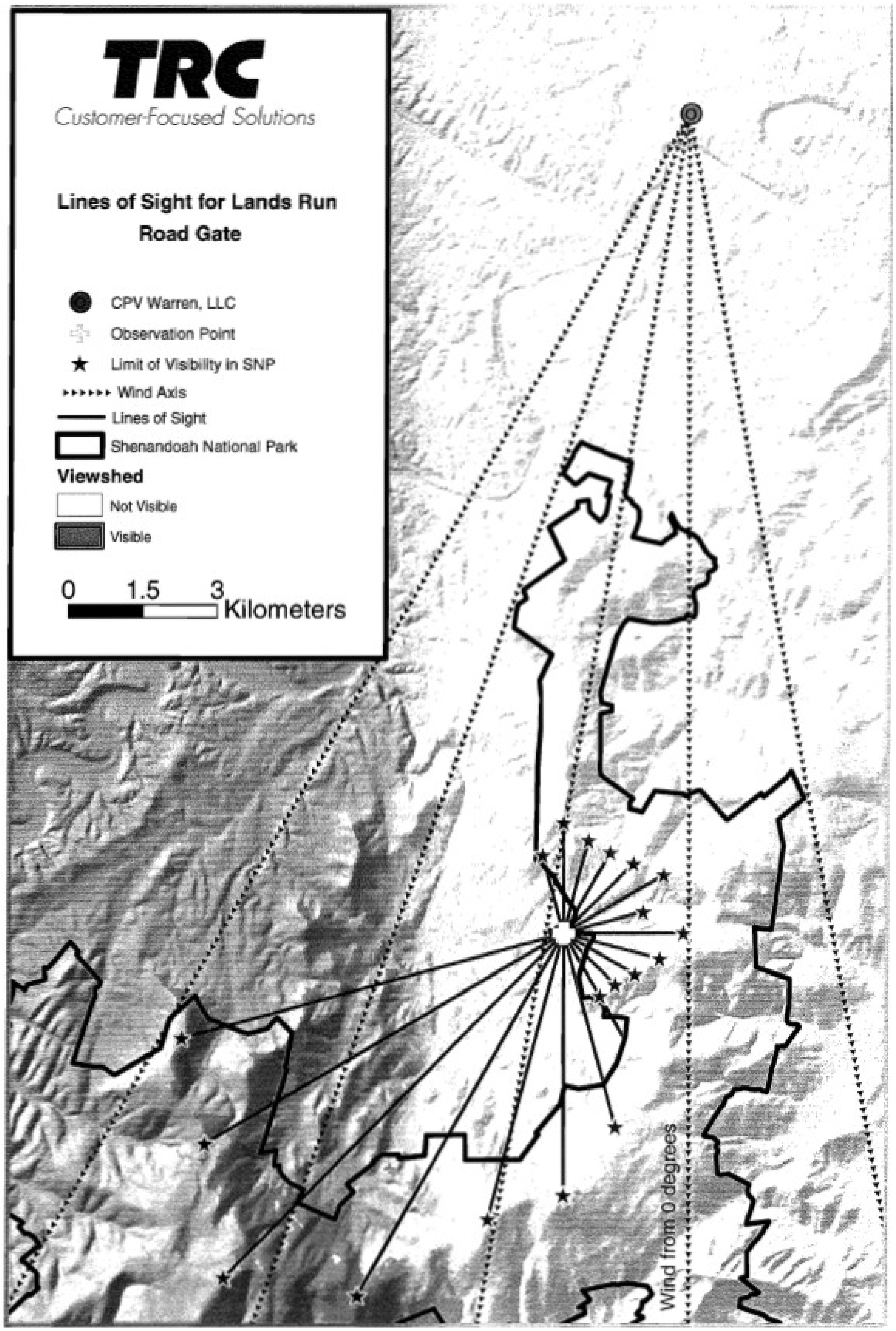


Figure 5-6 Lines of Sight for Lands Run Road Gate



5.3 Growth Analysis

A growth analysis examines the potential emissions from secondary sources associated with the proposed project. While these activities are not directly involved in project operation, the emissions involve those that can reasonably be expected to occur; for instance, industrial, commercial, and residential growth that will occur in the project area due to the project itself. Secondary emissions do not include any emissions which come directly from a mobile source, such as emissions from the tailpipe of any on-road motor vehicle or the propulsion of a train (USEPA 1990). They also do not include sources that do not impact the same general area as the source under review.

The work force expected for the project will range from 400 to 600 jobs during various phases of construction. It is expected that a significant regional construction force is already available to build the Project. Therefore, it is expected that no new housing, commercial or industrial construction will be necessary to support the Project during the two-year construction schedule. The Project will also require approximately 20 to 25 permanent positions. Individuals that already live in the region will perform a number of these jobs. For any new personnel moving to the area, no new housing requirements are expected. Further, due to the small number of new individuals expected to move onto the area to support the Project and existence of some commercial activity in the area, new commercial construction will not be necessary to support the Project's permanent work force. In addition, no significant level of industrial related support will be necessary for the Project, thus industrial growth is not expected.

Based on the growth expectations above, no new significant emissions from secondary growth during Project construction and operation are anticipated.

5.4 Soils and Vegetation Analysis

The Environmental Protection Agency (EPA) guidance document for soils and vegetation, *A Screening Procedure for the Impacts of Air Pollution Sources on Plants, Soils, and Animals (EPA 450/2-81-078),* was last updated in 1980 and does not necessarily represent the current state of knowledge. Therefore, the screening methodology provided in that document of comparing the air quality modeling emission results to the "vegetation sensitivity thresholds" will be supplemented with a more robust soils and vegetation analysis as described below.

<u>Vegetation Assessment</u>

As an indication of whether emissions from the proposed project will significantly impact the surrounding vegetation (i.e., cause acute or chronic exposure to each evaluated pollutant), the modeled emission concentrations will be compared against both a range of injury thresholds found in various peer-reviewed research articles that specifically examine effects of different pollutants on vegetation as well as established National Ambient Air Quality Standard (NAAQS) secondary standards. Since the NAAQS secondary standards were set to protect public welfare, including protection against damage to crops and vegetation, comparing the modeled emissions to these standards will provide some indication if potential impacts are likely to be significant. However, given that secondary standards for some criteria pollutants are under review, comparison to the secondary NAAQS may not be definitive.

Pollutant emissions examined will consist of sulfur dioxide (SO_2), nitrogen oxides (NO_X), particulate matter (PM) and carbon monoxide (CO). Modeled resultant modeled concentrations will be compared against the vegetation sensitivity thresholds listed in the aforementioned 1980 EPA guidance, secondary NAAQS, and plant injury thresholds found in the literature. Table 5-1 below illustrates injury threshold ranges determined through a review of available research.

Table 5-1 Injury Threshold for Vegetation

Pollutants	**Injury Threshold (Dose)**[1] ($\mu g/m^3$)	**NAAQS** ($\mu g/m^3$)	**EPA's 1980 Screening Concentration**[2] ($\mu g/m^3$)
SO_2	131-5,240 (8 hour)	1,300 (3 hour)	18 (annual)
	1,310 (4 hour)		786 (3 hour)
	393-3,930 (2 hour)		917 (1 hour)
NO_x (as NO_2)	280 – 38,000 (1 hour to long term)	100 (annual)	94 (annual)
			3,760 (4 hour)
			564 (1 month)
PM (as PM_{10})	See NAAQS	150 (24 hour)	None
		50 (annual)	
CO	None		1,800,000 (weekly)

1. Values suggested in the Spiritwood Station PSD permit application; see http://www.greatriverenergy.com/makingelectricity/newprojects/spiritwood_applicationsandreports.html

2. "A Screening Procedure for the Impacts of Air Pollution Sources on Plants, Soils, and Animals". EPA 450/2-81-078, December 1980

Soil Assessment

To determine whether the project emissions could adversely affect the soil in the vicinity of the project, the type of soil surrounding the project site will first be established. The soil type will be determined from data collected from the U.S. Department of Agriculture, National Resource Conservation Service's (NRCS), Soil Survey Geographic (SSGUGO) database[2] and the NRCS Web Soil Survey tool[3]. Soil types within Warren, Clarke, Frederick and Shenandoah Counties will be

[2] U.S. Department of Agriculture, National Resource Conservation Service's (NRCS), Soil Survey Geographic (SSGUGO) database . Accessed 17 December 2009. http://soils.usda.gov/survey/geography/ssurgo/

[3] U.S. Department of Agriculture, National Resource Conservation Service's Web Soil Survey Tool. Accessed 17 December 2009. http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm

examined. These counties were chosen because the project site is within Warren County, and Clarke, Frederick, and Shenandoah Counties are either within a 10 km radius of the project site or will be used to represent typical soil type within Shenandoah National Park. Preliminary determinations indicate that within Warren County, various loams are one of the predominant soil textures. The evaluation will be based on the predominate soil type and its ability to absorb the acidifying effects of pollutant emissions such as SO_2 and NO_x as provided in EPA's 1980 guidance supplemented with threshold levels found in the literature.

5.5 $PM_{2.5}$ NAAQS Compliance Analysis

EPA has not yet provided national guidance for modeling compliance with the $PM_{2.5}$ NAAQS. Until recently, EPA accepted modeled compliance with the PM_{10} NAAQS as a surrogate for indicating compliance with the $PM_{2.5}$ NAAQS, in accordance with a 1997 Office of Air Quality Planning and Standards memo that provided EPA guidance on this matter. However, recent rulings by EPA have resulted in revised guidance for permit applicants to attempt to address the issue of modeled compliance with the $PM_{2.5}$ NAAQS directly, even in the absence of EPA modeling guidance.

In response to a request from VA DEQ to propose an approach for modeling compliance with the $PM_{2.5}$ NAAQS, we propose a tiered approach. One key issue with demonstrating compliance with the $PM_{2.5}$ NAAQS is that background concentrations typically constitute a large fraction of the NAAQS, and are often much higher than the project impacts. EPA modeling guidance in 40 CFR Part 51, Appendix W addresses situations where background concentrations are not dominant, and this guidance has not been updated to address the $PM_{2.5}$ NAAQS cases in which background concentrations are dominant. In fact, there is no substantial discussion in the EPA modeling guidance that addresses $PM_{2.5}$ modeling. One key issue is that the assumption of high background concentrations on every modeled day can result in false indications of potential modeled NAAQS violations.

Another modeling issue that is unresolved for compliance with the $PM_{2.5}$ NAAQS is that EPA has not yet defined the Significant Impact Levels (SILs) that are applicable for $PM_{2.5}$. These SILs are proposed in the September 21, 2007 Federal Register (72 FR 54139-54140), which also establishes the legal basis for SILs to determine whether a proposed source will cause or contribute to a NAAQS violation. Therefore, we propose to adopt the option with the overall lowest EPA-proposed values for both PSD Class I and II modeling in order to define the extent to which receptors need to be placed for cumulative modeling. Support for the use of the lowest proposed SIL comes from Mr. Dan DeRoeck of EPA, who indicated (2009) that the final EPA rule would have a SIL within the range of the proposed options. Our use of the lowest proposed SILs is a conservative approach. The SILs to be used for the permit application are the EPA-proposed Option 3 values of 1.2 $\mu g/m^3$ and 0.3 $\mu g/m^3$ for the daily and annual averages for PSD Class II modeling, and 0.07 $\mu g/m^3$ and 0.06 $\mu g/m^3$ for daily and annual averages for PSD Class I modeling. Cumulative NAAQS modeling will be limited to those receptors for which the SILs are exceeded for modeling of the project impacts alone.

Our Tier 1 (conservative) approach for any cumulative modeling of $PM_{2.5}$ is to adopt a conservatively high 98th percentile daily monitored background concentration, averaged over the period of 2006-2008, from the nearby representative $PM_{2.5}$ monitor at Luray Caverns airport. This concentration will be assumed to apply for <u>each</u> modeled day at all receptors.

The modeled impact for $PM_{2.5}$ NAAQS compliance will be done in three 3-year groups, consistent with the 3-year period used to define compliance with the NAAQS. The three groups will consist of meteorological years 1988-1990, 1989-1991, and 1990-1992. For each 3-year period, the modeled annual concentration of interest will be the highest 3-year average at each receptor. Similarly, the modeled 24-hour concentration of interest will be the highest average of the annual 98^{th} percentile (H8H) concentrations at each receptor. The overall peak modeled value of interest over 3 years will be the highest of the results for each of the 3-year periods.

In addition to the modeled project impacts plus a regional background value, we will also add impacts from nearby sources with emissions high enough and close enough to likely cause a significant concentration gradient within an area referred to as the "Significant Impact Area", or SIA. This area is defined for Class II areas as the furthest distance from the source (up to 50 km) for which a peak modeled impact at a receptor exceeds the Class II SIL for either daily or annual averages. For Class I receptors, this would be defined similarly, except that receptors are confined to the Class I area, the Class I SILs are used, and there is still a 50-km maximum extent of the SIA. Consistent with previous guidance from Mr. Don Shepherd of the National Park Service (2006), we propose to use a "Q/D" approach for screening out sources (using facility-total emissions) beyond the extent of the SIA in both Class I and Class II areas.

The methodology that will be followed for the cumulative modeling analysis for the Class II areas is described as follows:

- All agency-identified sources within the SIA will be modeled with the exception of very small sources (we propose total permitted short-term emissions less than 5 ton per year), whose impacts would be accounted for by regional background.
- For sources beyond the extent of the SIA, define D as the distance in km of a candidate nearby source beyond the SIA, and Q as the permitted short-term emissions expressed in tons per year (TPY). Since for $PM_{2.5}$, the significant emission increase threshold is 10 TPY, define Q/D such that at a distance of 50 km, the threshold short-term emission rate for screening out is 10 TPY. For this case, a Q/D value of 0.2 will be applied for $PM_{2.5}$, although the exclusion of nominal sources of 5 TPY or less will be used beyond the SIA as well.
- Any source identified as a fugitive source located 10 km beyond the SIA will be eliminated.

The methodology that will be followed for the cumulative modeling analysis for the Class I areas is described as follows:

- All agency-identified sources within 50 km of Shenandoah with very small emissions (facility totals less than 5 tons per year), whose impacts would be accounted for by regional background will not be included in the cumulative modeling.

- For sources within 50 km of Shenandoah whose facility emission totals exceed 5 TPY a Q/D screening approach was applied, where D is defined as the shortest distance in km of a candidate nearby source to Shenandoah NP and Q as the permitted short-term facility total emissions expressed in tons per year (TPY). Since for $PM_{2.5}$, the significant emission increase threshold is 10 TPY, define Q/D such that at a distance of 50 km, the threshold short-term emission rate for screening out is 10 TPY. For this case, a Q/D value of 0.2 will be applied for $PM_{2.5}$, although the exclusion of nominal sources of 5TPY or less will be used beyond the SIA as well.

- Upon completing the Q/D screening analysis, the sources with emissions greater than 5 TPY that would have screened out will be conservatively modeled.

Because there are expected to be data gaps in some of the emissions inventory records, a conservative approach will be followed as described below:

- Any missing stack parameters in the inventories will be filled with the 2005 NEI database.
- For the sources/facilities that cannot be found in 2005 NEI database, missing stack parameters will be filled with appropriate stack parameters to represent a worst-case modeling scenario - 10 ft for the stack height, 68°F for the stack exit temperature, 0.0003 fps for the stack exit velocity and 0.003 ft for the stack diameter

If this conservative approach of combining peak modeled and monitored background concentrations shows total concentrations below the $PM_{2.5}$ NAAQS, then no further analysis will be needed, even though the total modeled impacts will likely be overstated. In the event that the modeled impacts with this Tier 1 approach exceed the NAAQS, it will likely be due to the assumption of a conservatively high background concentration for every day modeled. In that case, Dominion reserves the right to refine the monitored background assumed to be applicable for each modeled day. This refinement will be proposed as a supplement to this protocol, and may involve the use of seasonal background values, or perhaps background values associated with specific meteorological flow regimes.

5.6 Air Toxics Analysis

As stated in Section 2.3.2, modeling analyses will be performed for the sources subject to requirements under 9 VAC 5-60-300 after guidance received from the VA DEQ VRO and for which pollutant emission levels are above the VA DEQ exemption level. The modeled concentrations will be compared to the corresponding pollutant Significant Ambient Air Concentration (SAAC).

5.7 Conversion of NO to NO_2

To estimate maximum annual NO_2 concentrations, Dominion proposes to use the multi-tiered approach documented in EPA's Guideline on Air Quality Models. A multi-tiered approach to estimate annual average concentrations of NO_2 from the proposed turbines and auxiliary equipment for New Source Review, PSD, and SIP planning will be used. For the initial screen (Tier 1), total conversion of NO to NO_2 will be assumed and the predicted annual average concentrations will be compared to the appropriate SILs, NAAQS, PSD increments, and PSD ambient air quality monitoring de minimis concentrations. If, using this conservative approach, predicted concentrations exceed these levels a more refined (Tier 2) approach will be used. For the Tier 2 analysis, the Tier 1 estimates will be multiplied by the annual national default value of 0.75 (40 CFR 51 Appendix W §5.2.4(c)).

6.0 Submittal of Analysis Results

The findings of the modeling analyses will be submitted to VA DEQ in a formal report for review and approval. The report will address the following:

- Source Data: Source data required for evaluation of project impacts will be provided. This will include criteria pollutant emission rates and stack exhaust parameters.
- Choice of Models: The chosen models including version numbers and selected options will be discussed.
- Receptor Data: A plot of the receptor grid used in the AERMOD analysis will be provided with the final permitting document.
- Meteorology: The meteorological conditions used in the analysis will be documented. The use of Dulles Airport, Virginia and Sterling, Virginia upper air meteorological data will be discussed.
- Modeling Summary: Results of the modeling analyses for all operating scenarios will be documented and summarized.
- Compliance with NAAQS and PSD Increments: A demonstration of compliance with these standards will be presented and supported in the report in text, tabular and/or graphical format.

Model Output and Databases: The model input and output files will be provided to VA DEQ on CD/DVD-ROM. Also, BPIP-Prime input and output files will be provided. The final modeling report will also include graphics (e.g., contour maps) that show the extent of the air quality impacts for the worst case year for each pollutant and averaging period for each turbine. The figures will utilize a base map that is readily understandable by the general public. Each map will clearly identify the proposed plant location relative to these air quality impacts.

7.0 References

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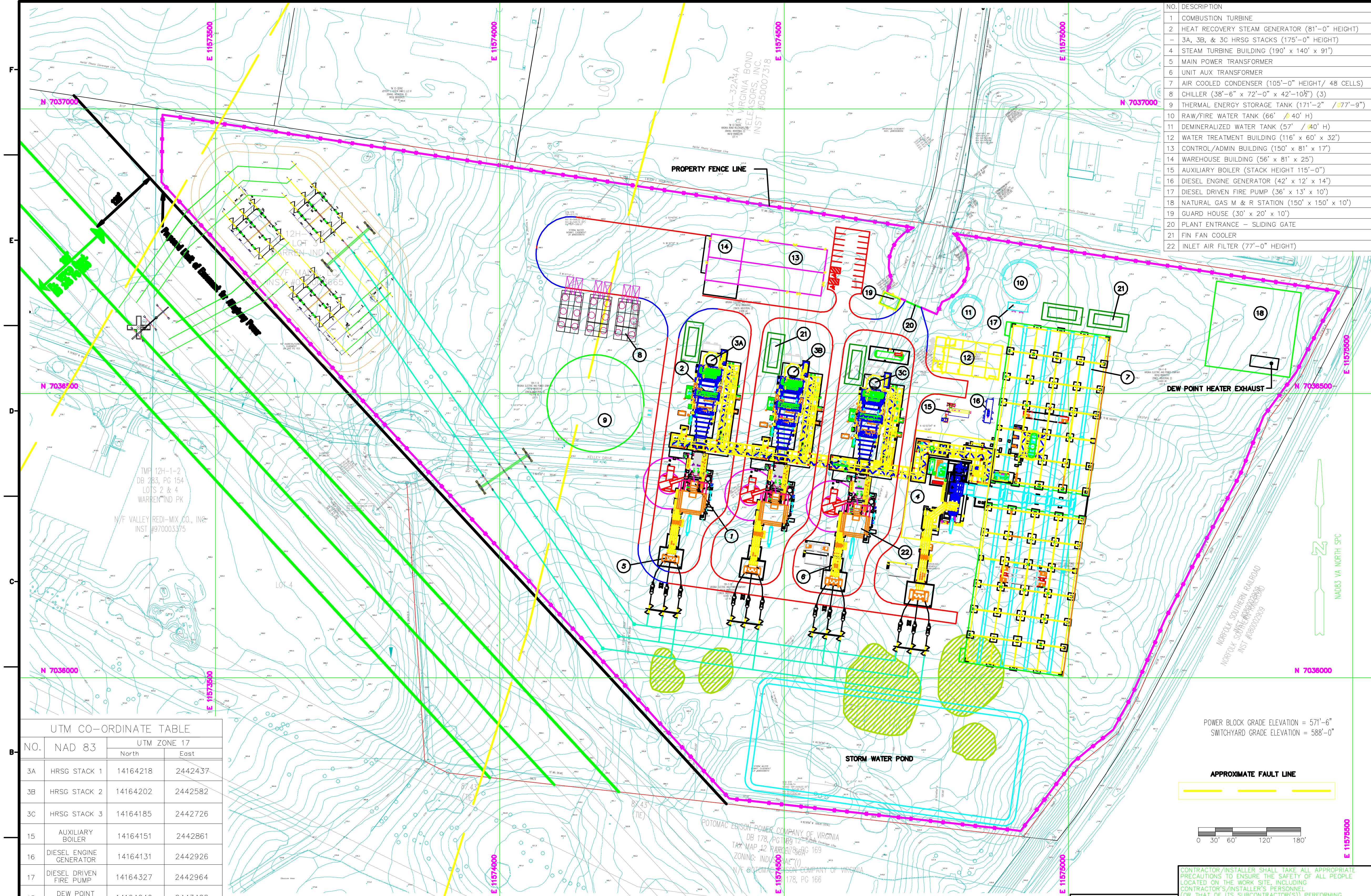
Appendix A

Preliminary Site Plans



NO.	DESCRIPTION
1	COMBUSTION TURBINE
2	HEAT RECOVERY STEAM GENERATOR (81'–0" HEIGHT)
–	3A, 3B, & 3C HRSG STACKS (175'–0" HEIGHT)
4	STEAM TURBINE BUILDING (190' x 140' x 91')
5	MAIN POWER TRANSFORMER
6	UNIT AUX TRANSFORMER
7	AIR COOLED CONDENSER (105'–0" HEIGHT/ 48 CELLS)
8	CHILLER (38'–6" x 72'–0" x 42'–10½") (3)
9	THERMAL ENERGY STORAGE TANK (171'–2" / Ø77'–9")
10	RAW/FIRE WATER TANK (66' / Ø 40' H)
11	DEMINERALIZED WATER TANK (57' / Ø40' H)
12	WATER TREATMENT BUILDING (116' x 60' x 32')
13	CONTROL/ADMIN BUILDING (150' x 81' x 17')
14	WAREHOUSE BUILDING (56' x 81' x 25')
15	AUXILIARY BOILER (STACK HEIGHT 115'–0")
16	DIESEL ENGINE GENERATOR (42' x 12' x 14')
17	DIESEL DRIVEN FIRE PUMP (36' x 13' x 10')
18	NATURAL GAS M & R STATION (150' x 150' x 10')
19	GUARD HOUSE (30' x 20' x 10')
20	PLANT ENTRANCE – SLIDING GATE
21	FIN FAN COOLER
22	INLET AIR FILTER (77'–0" HEIGHT)

UTM CO–ORDINATE TABLE

NO.	NAD 83	UTM ZONE 17 North	UTM ZONE 17 East
3A	HRSG STACK 1	14164218	2442437
3B	HRSG STACK 2	14164202	2442582
3C	HRSG STACK 3	14164185	2442726
15	AUXILIARY BOILER	14164151	2442861
16	DIESEL ENGINE GENERATOR	14164131	2442926
17	DIESEL DRIVEN FIRE PUMP	14164327	2442964
18	DEW POINT HEATER	14164240	2443422

CONTRACTOR/INSTALLER SHALL TAKE ALL APPROPRIATE PRECAUTIONS TO ENSURE THE SAFETY OF ALL PEOPLE LOCATED ON THE WORK SITE, INCLUDING CONTRACTOR'S/INSTALLER'S PERSONNEL (OR THAT OF ITS SUBCONTRACTOR(S)) PERFORMING THE WORK.

FILENAME: M–005B.DGN

DRAWING RELEASE RECORD

REV.	DATE REL'D.	PREPARED	REVIEWED	APPROVED	PURPOSE

DRAWING RELEASE RECORD

REV.	DATE REL'D.	PREPARED	REVIEWED	APPROVED	PURPOSE
A	10/16/2009	R. MILLER	J. G. GATZ	———	FOR AIR MODELING
B	10/23/2009	R. MILLER	J. G. GATZ	———	FOR AIR MODELING
C	10/29/2009	R. MILLER	J. G. GATZ	———	FOR AIR MODELING
D	11/12/2009	R. MILLER	J. G. GATZ	———	FOR AIR MODELING

SCALE 1" = 60'

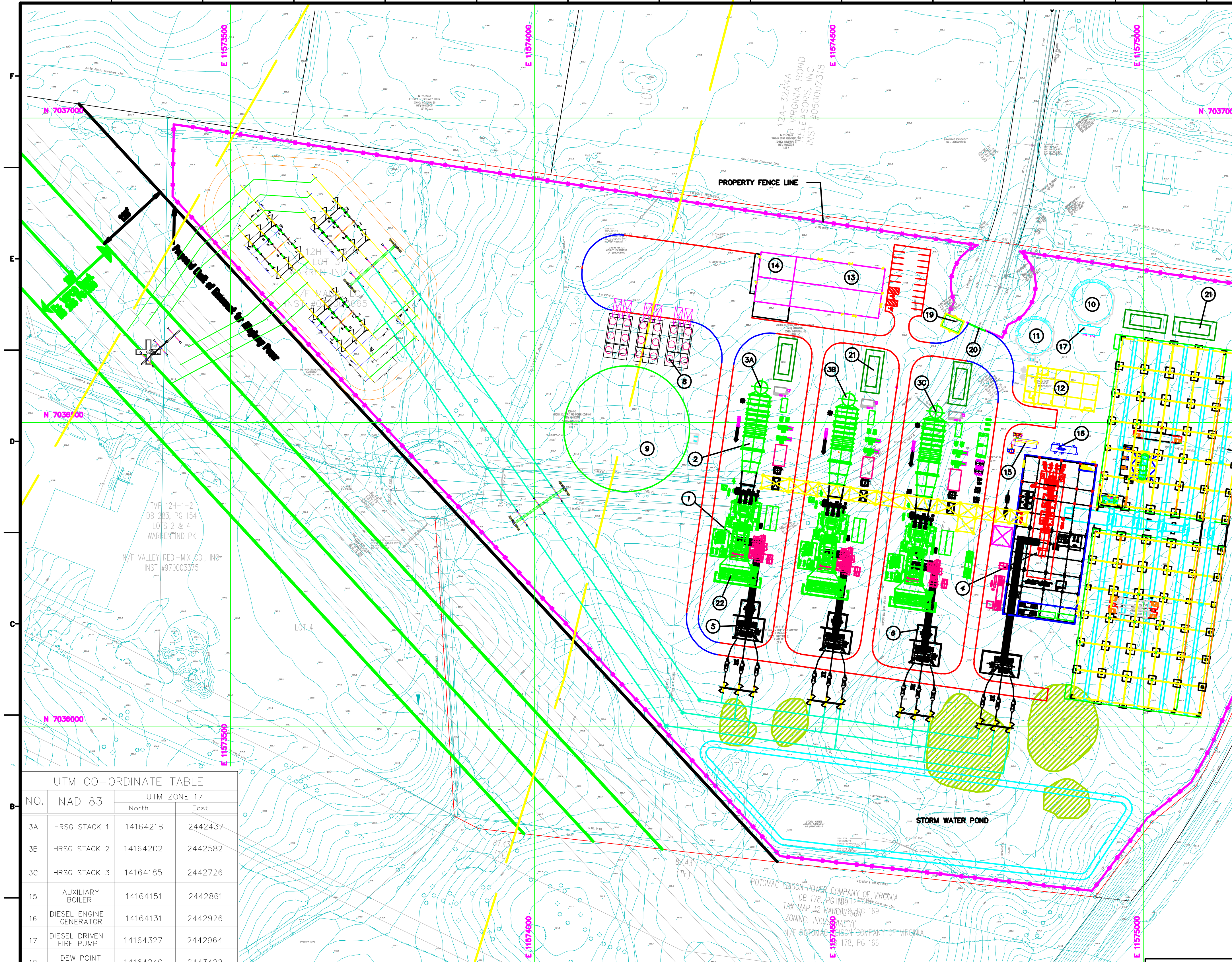
PROJECT NUMBER 12388–002

PRELIMINARY GENERAL ARRANGEMENT SIEMENS 5000F COMBINED CYCLE 3x3x1 DOMINION WARREN COUNTY

Sargent & Lundy LLC

DRAWING NO. M–005 REV. D

SHEET OF



NO.	DESCRIPTION
1	COMBUSTION TURBINE
2	HEAT RECOVERY STEAM GENERATOR (95'–0" HEIGHT)
–	3A, 3B, & 3C HRSG STACKS (175'–0" HEIGHT)
4	STEAM TURBINE BUILDING (265' x 120' x 96')
5	MAIN POWER TRANSFORMER
6	UNIT AUX TRANSFORMER
7	AIR COOLED CONDENSER (105'–0" HEIGHT/ 60 CELLS)
8	CHILLER (38'–6" x 72'–0" x 42'–10½") (3)
9	THERMAL ENERGY STORAGE TANK (206'–8" /Ø 72'–5")
10	RAW/FIRE WATER TANK (66' /Ø 40' H)
11	DEMINERALIZED WATER TANK (57' /Ø 40' H)
12	WATER TREATMENT BUILDING (116' x 60' x 32')
13	CONTROL/ADMIN BUILDING (150' x 81' x 17')
14	WAREHOUSE BUILDING (56' x 81' x 25')
15	AUXILIARY BOILER (STACK HEIGHT 115'–0")
16	DIESEL ENGINE GENERATOR (42' x 12' x 14')
17	DIESEL DRIVEN FIRE PUMP (36' x 13' x 10')
18	NATURAL GAS M & R STATION (150' x 150' x 10')
19	GUARD HOUSE (30' x 20' x 10')
20	PLANT ENTRANCE – SLIDING GATE
21	FIN FAN COOLER
22	INLET AIR FILTER (82'–0" HEIGHT)

UTM CO–ORDINATE TABLE

NO.	NAD 83	UTM ZONE 17 North	UTM ZONE 17 East
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FILENAME: M–006B.DGN

DRAWING RELEASE RECORD

REV.	DATE REL'D.	PREPARED	REVIEWED	APPROVED	PURPOSE

DRAWING RELEASE RECORD

REV.	DATE REL'D.	PREPARED	REVIEWED	APPROVED	PURPOSE
A	10/16/2009	R. MILLER	J. G. GATZ	———	FOR AIR MODELING
B	10/23/2009	R. MILLER	J. G. GATZ	———	FOR AIR MODELING
C	10/29/2009	R. MILLER	J. G. GATZ	———	FOR AIR MODELING
D	11/12/2009	R. MILLER	J. G. GATZ	———	FOR AIR MODELING

SCALE 1" = 60'

PROJECT NUMBER 12388–002

PRELIMINARY GENERAL ARRANGEMENT MHI 501G1 COMBINED CYCLE 3x3x1 DOMINION WARREN COUNTY

Sargent & Lundy LLC

DRAWING NO. M–006 REV. D

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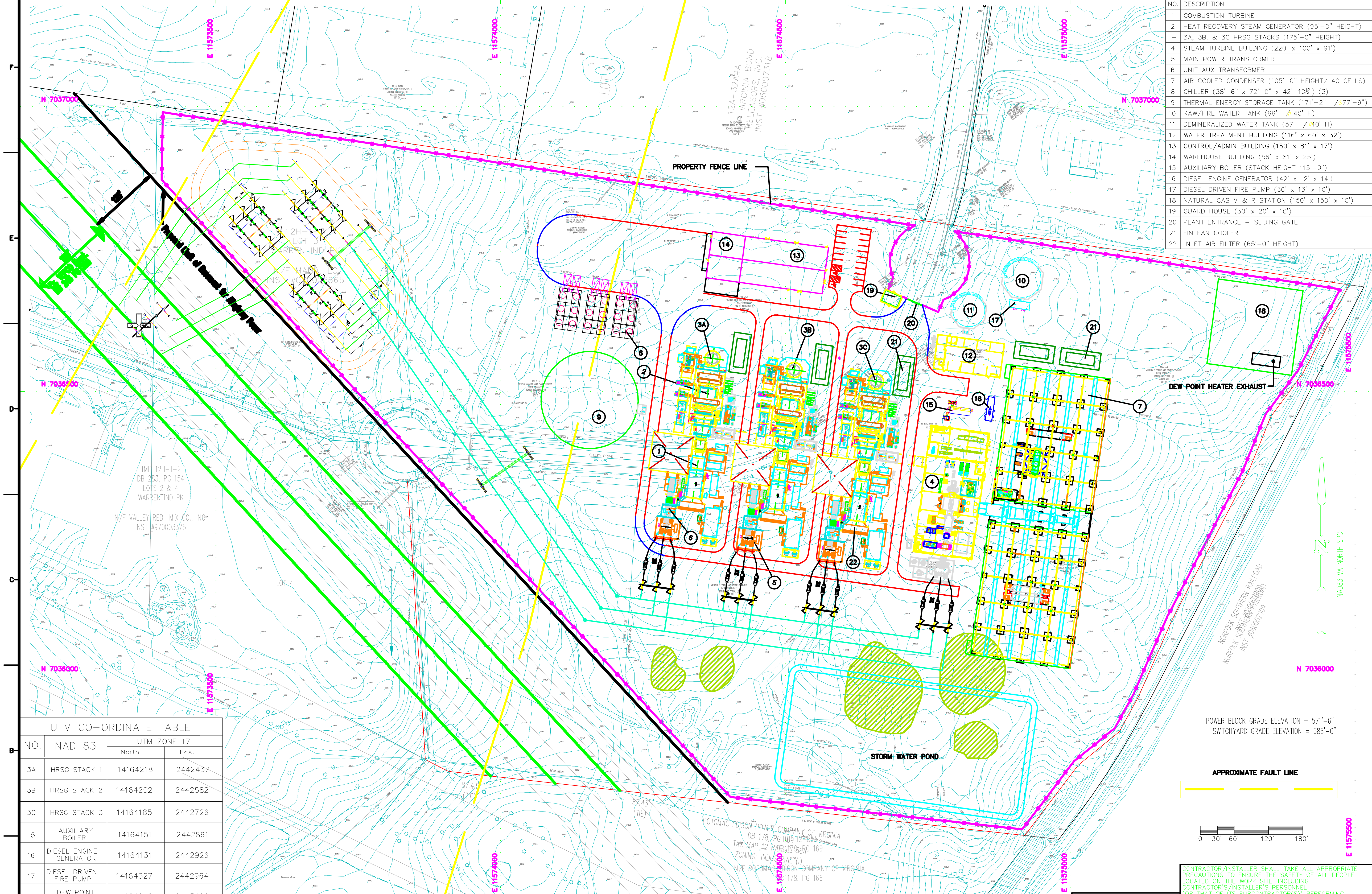

NO.	DESCRIPTION
1	COMBUSTION TURBINE
2	HEAT RECOVERY STEAM GENERATOR (95'–0" HEIGHT)
–	3A, 3B, & 3C HRSG STACKS (175'–0" HEIGHT)
4	STEAM TURBINE BUILDING (220' x 100' x 91')
5	MAIN POWER TRANSFORMER
6	UNIT AUX TRANSFORMER
7	AIR COOLED CONDENSER (105'–0" HEIGHT/ 40 CELLS)
8	CHILLER (38'–6" x 72'–0" x 42'–10½") (3)
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11	DEMINERALIZED WATER TANK (57' /Ø40' H)
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UTM CO-ORDINATE TABLE

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FILENAME: M–004C.DGN

DRAWING RELEASE RECORD

REV.	DATE REL'D.	PREPARED	REVIEWED	APPROVED	PURPOSE
A	10/16/2009	R. MILLER	J. G. GATZ		FOR AIR MODELING
B	10/23/2009	R. MILLER	J. G. GATZ		FOR AIR MODELING
C	10/29/2009	R. MILLER	J. G. GATZ		FOR AIR MODELING
D	11/12/2009	R. MILLER	J. G. GATZ		FOR AIR MODELING

SCALE 1"= 60'

PROJECT NUMBER 12388–002

PRELIMINARY GENERAL ARRANGEMENT GE 7FA COMBINED CYCLE 3x3x1 DOMINION WARREN COUNTY

Sargent & Lundy LLC

DRAWING NO. M–004 REV. D

SHEET OF

Appendix B

Richards et al. paper on "Refinements of Plume Visibility Thresholds for Apparent Plume Width"

Refinements of Plume Visibility Thresholds for Apparent Plume Width

Paper #55

L. Willard Richards and Jeffry D. Prouty

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Steven E. Zell, P.E. and Pietro A. Catizone, Q.E.P.

TRC Environmental Corporation, 21 Griffin Road North, Windsor, CT 06095

ABSTRACT

Analyses are required by the Clean Air Act Amendments to assess whether or not a plume from a new or modified major source will be visually perceptible in a nearby Class I area. Key data used in these analyses include the human visual perception thresholds for contrast and color difference. Until now, the apparent width of the plume has not been considered in these regulatory analyses. Existing data for contrast perception thresholds and new data for color difference perception thresholds are used to show that the apparent width of the plume is an important factor. Perception thresholds for contrast and color difference that account for the apparent width of the plume are described.

INTRODUCTION

The Clean Air Act Amendments require that new or modified major sources of emission of sulfur dioxide, nitrogen oxides, and/or particulate matter evaluate the effects of plumes on visibility in nearby Class I areas. Permit applications are reviewed for visibility impairment by the Federal Land Manager for the Class I area.

For Class I areas within 50 km of the source, analyses must be performed to assess whether the plume from the source will be visually perceptible in the Class I area. The U.S. Environmental Protection Agency (EPA) has prescribed a methodology for this assessment, which consists of three levels of analysis.[1] If a simple screening analysis using conservative assumptions demonstrates insignificant impacts, the more complex analysis need not be performed. The third level of analysis requires the use of the PLUVUE II plume visibility model.

PLUVUE II calculates the transport, dispersion, and transformation of the source emissions in the atmosphere. The model uses these data to calculate the optical properties of the plume. Parameters related to human perception, such as contrast and color difference, are then calculated for the plume. The perception parameters calculated by the model are used to assess whether or not the plume would be visually perceptible. Until now, even though the relevance of the apparent width has been recognized,[2] the apparent width of the plume has not been considered in regulatory assessments. This paper presents data for the dependence of contrast and color difference perception thresholds on the apparent width of a pattern such as a plume, and recommends perception thresholds that account for this factor. The effects of using these perception thresholds in the assessment of the visual effects of a point source in a Class I area are presented in an accompanying paper.[3]

PLUVUE II MODEL

The original PLUVUE model was released in 1978.[4] It uses the Briggs plume rise formulas and a terrain-following, straight-line Gaussian model to calculate the transport and dispersion of the stack emissions using hourly meteorological data. The model calculates particle formation in the plume from the photochemical oxidation of nitrogen and sulfur oxide emissions. Seasonal averages are used for the background concentrations of pollutant gases. Background particle concentrations are selected to represent the clearest days. Clouds and natural visibility obscuration by precipitation or fog are not addressed by the model.

Observer based calculations are typically used for regulatory analyses. Observer locations are selected in the Class I area, and, for each observer location, a series of downwind distances are selected. The line from the observer to the plume centerline at a selected downwind distance determines the sight path used for the optical calculations.

The optical calculations in PLUVUE contain fewer simplifications and approximations than the transport and dispersion calculations. They are performed at each of 39 wavelengths throughout the visible spectrum, and then these results are combined to calculate perception parameters. PLUVUE II was released in 1984[5] and added a simplified radiative transfer calculation to determine how sunlight is multiply scattered and partially absorbed in the Earth's atmosphere. PLUVUE II uses that information to determine the radiance of the sky or the background terrain in the direction of the sight path in the absence of the plume. The plume is then introduced into the sight path. Both the extinction of light from the background sky or terrain as it passes through the particles and nitrogen dioxide in the plume to the observer and the scattering of light into the sight path by the plume are included in the calculations. Finally, the Commission Internationale de l'Eclairage (CIE) standard observer equations are used to calculate the CIE X, Y, and Z coordinates both with and without the plume from the 39-wavelength data. These CIE coordinates are then used to calculate the contrast and color difference caused by the plume. The equations for the contrast and color difference calculations are at the end of the Appendix.

The assessment regarding whether or not the contrast and color difference calculated by PLUVUE II are humanly perceptible is separate from the model. The selection of the perception thresholds used to make that assessment is the topic of this paper.

CONTRAST PERCEPTION THRESHOLD

The contrast of a plume indicates the amount by which the centerline of the plume appears lighter or darker than the background behind the plume would appear if the plume were not present. The contrast of an object against its background is one of the best indicators of whether or not the object is visually perceptible. The literature contains data from many studies on the human perception threshold for contrast.

The analysis that follows is based primarily on the data reported by Howell and Hess[6] because the original EPA guidance[1] as well as the current FLAG guidance[7] for contrast thresholds are based on these data. Additional information from experiments sponsored by the National Park Service (NPS) is cited as the basis for calculating the apparent width of a plume.

Figure 1. Figure from the EPA Workbook[1] showing the dependence of the threshold contrast on the apparent width of the plume.

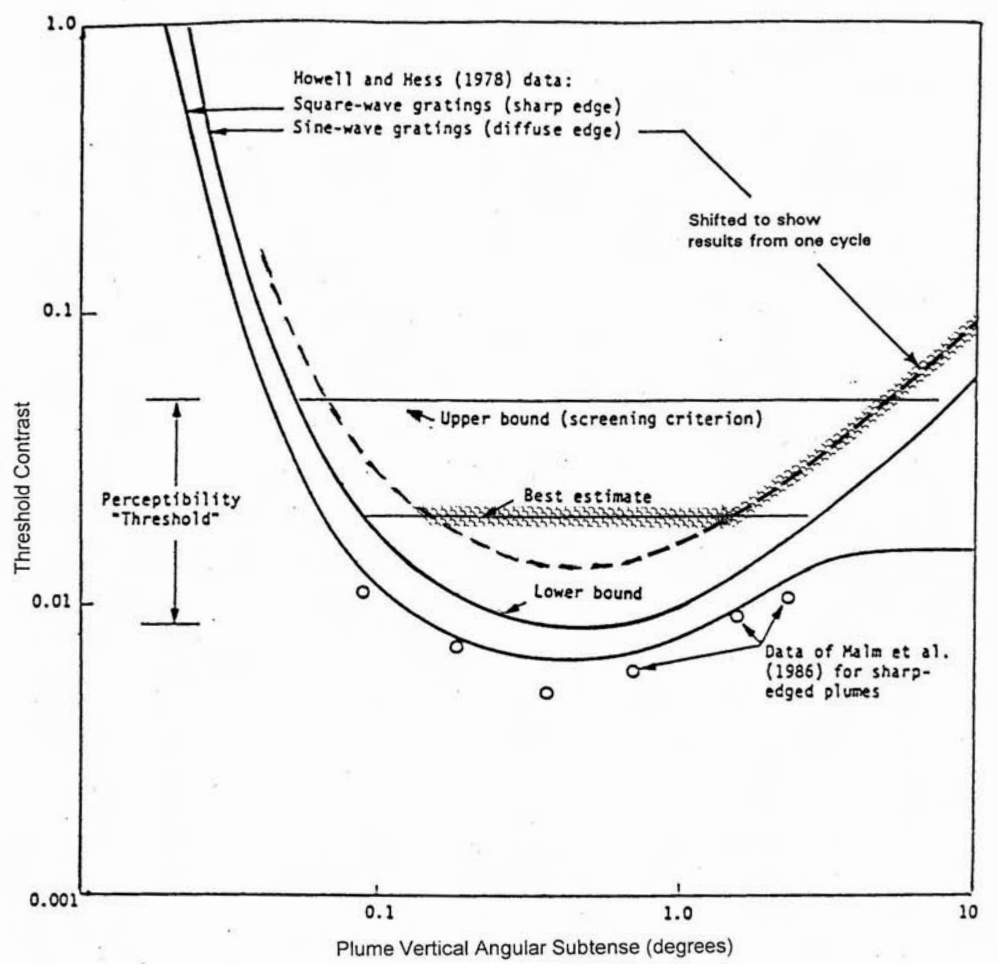


Figure 1 is copied from the original EPA guidance,[1] and the dashed and the cross-hatched lines have been added. The two solid-line curves summarize the observations of Howell and Hess[6] for sine-wave and square- wave patterns. The experiments reported by Howell and Hess were performed by generating sine-wave patterns on a cathode-ray tube (CRT) surrounded by a large area of the same color and with a luminance equal to the average luminance of the sine-wave pattern. The observers adjusted the contrast of each sine-wave pattern to determine the threshold contrast. The observers were in a laboratory setting with a controlled environment, were intent on determining the threshold contrast of a known pattern, and could increase the contrast of the pattern at will to refresh their memory of the pattern to be perceived.

These experiments explored the effects of the angle subtended by one cycle of the sine-wave pattern as well as the number of cycles in the pattern on the threshold contrast. The Howell and Hess data used as the basis for the EPA guidance[1] are for a sine-wave pattern with five full sine-wave cycles. This pattern is not a good representation of the luminance profile of a Gaussian plume. The best approximation of a Gaussian plume that is included in the Howell and Hess experiments is a sine-wave pattern with one full cycle. This pattern can be thought of as representing two plumes side-by side, one bright and the other dark, with equal widths and contrasts of equal magnitude. The width of each of these plumes is one-half of a cycle.

Howell and Hess report data by two observers that can be used to compare the threshold contrast for one-cycle and five-cycle sine-wave patterns. The data from one of the observers indicate that the contrast threshold was a factor of 1.7 larger for the one-cycle pattern than the five-cycle pattern and the data from the other observer indicate that the factor is 2.1. Also, another correction to the Howell and Hess data for wide plumes can be justified. For wide plumes, the wider the plume, the greater the threshold contrast. Thus, it is reasonable to expect that the threshold contrast for a plume that subtends an angle equal to that of a full cycle of a sine wave will be greater than for the light and dark plumes side-by-side, each of which subtends an angle half as great. The experimental data reported by Howell and Hess do not contain enough information to estimate the magnitude of this additional correction.

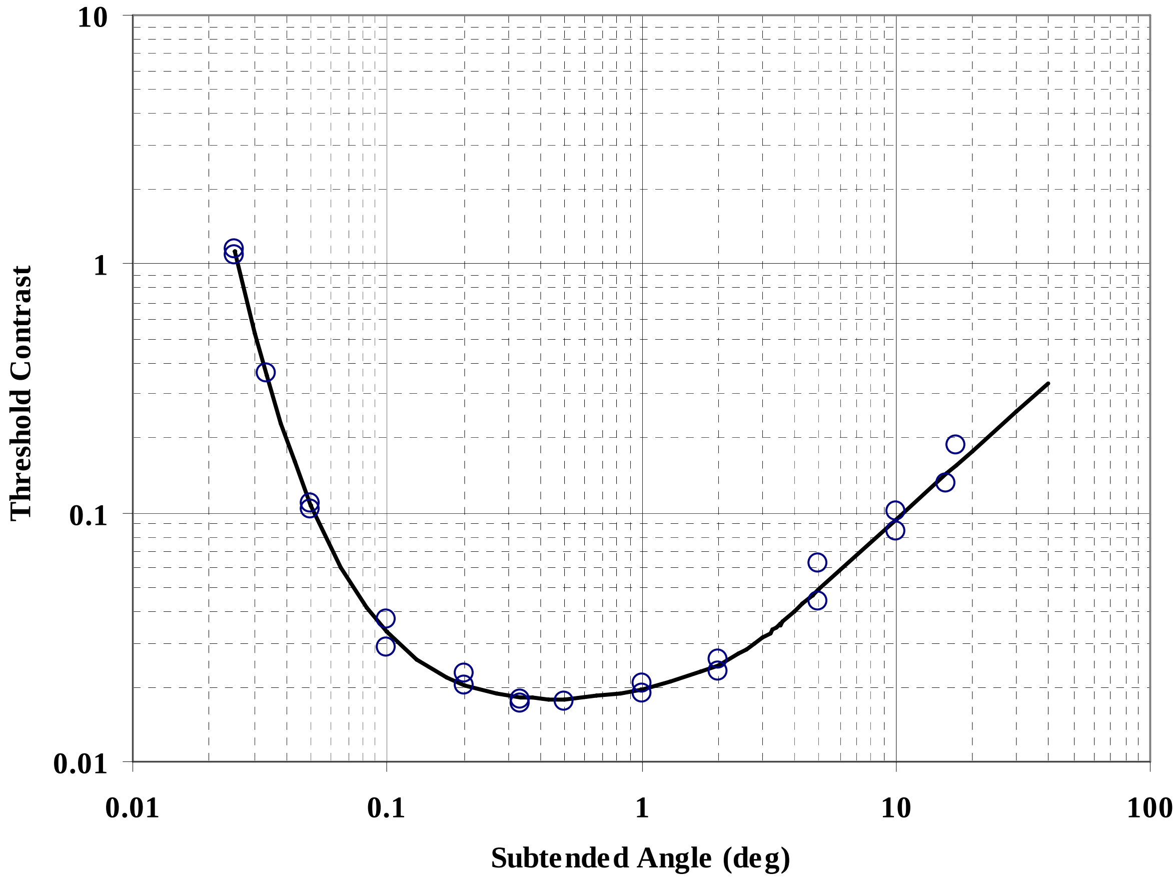
The dashed line in Figure 1 has been added to show the effect of adjusting the Howell and Hess data for five-cycle sine-wave patterns upward by a factor of two. The data points in Figure 2 show all their observations for five-cycle sine-wave patterns after this adjustment. The factor of two is a rounded number within the range of factors derived from the data from two observers that converts five-cycle to one-cycle sine wave data. This factor is conservative because it makes no additional correction for the fact that the Howell and Hess observations for a one-cycle sine wave pattern are equivalent to viewing side-by-side light and dark plumes.

The NPS sponsored research on the perception thresholds for square-wave and sine-wave plumes.[8] In these experiments, a panel of trained observers viewed a screen on which slides were projected. The slides were completely uniform, except for a dark, horizontal band representing a plume or a band of haze. In these experiments, the luminance of the surround was equal to the maximum luminance in the sine-wave pattern, and the plume or layered haze was represented by one full cycle, from the maximum to the minimum and back to the maximum luminance. When relating these data to Gaussian plumes, the width of one cycle of the sine-wave pattern was equated to four times sigma, where sigma is the Gaussian dispersion parameter used in the PLUVUE II model.[9] That relationship is used in this paper.

Ross et al.[8] state:

> "Only one width haze was presented during each session because in pretesting it was determined that when widths were mixed within a session, subjects were engaging in

Figure 2. Observations of Howell and Hess[6] of the dependence of the threshold contrast of five-cycle sine-wave patterns as a function of the apparent width of one cycle. The threshold contrasts have been increased by a factor of two as described in the text.



search behaviors which were not always appropriate and often became confused with where attention should be focused."

This indicates that if the panel of observers did not know in advance the pattern they were expected to see, they did not obtain appropriate results. In both of the controlled laboratory studies discussed above, the observers knew in advance the pattern they were expected to see and were intent on their task. These factors make the threshold contrast lower than for observers in the real world who do not know what pattern to expect.

The curved line in Figure 2 shows the result of a fourth-order polynomial regression of the logarithm of the contrast threshold data as a function of the logarithm of the subtended angle φ for observations at subtended angles equal to and less than five degrees. Equation 1 is the equation for this curve, which applies for both negative contrasts (dark plumes) and positive contrasts (bright plumes):

$$\log|C| = -1.71 + 0.21(\log\phi) + 0.31(\log\phi)^2 + 0.18(\log\phi)^3 + 0.31(\log\phi)^4 \quad \text{for } \phi \le 3.5 \text{ deg} \quad (1)$$

where |C| is the absolute value of the contrast and log is the base 10 logarithm. Figure 2 shows that this curve fits the data points to well within the experimental error. It was not possible to find a simple polynomial to fit all the observations.

The data for subtended angles equal to or greater than five degrees can be fit by a straight line, which intersects the curve. At the intersection, the curve and straight line have different slopes, and this would cause a kink if the curves were joined at this point. Instead, the curves were joined at a subtended angle of 3.5 degrees, where they have the same slope. For the curves to intersect at this point, it was necessary to decrease the linear regression intercept of the straight line by an amount equal to 13% of the standard error in its value. This change is well within the experimental error. It is also conservative, i.e., it lowers the threshold contrast. The result is shown by the straight line in Figure 2 and is represented by Equation 2:

$$\log|C| = -1.95 + 0.92(\log\phi) \qquad \text{for } \phi \ge 3.5 \text{ deg} \qquad (2)$$

It is recommended that Equations 1 and 2 be used to determine the threshold contrast of a plume instead of the constant value of |C| = 0.02, which is used in the original EPA[1] and current FLAG[7] guidance. Methods for calculating the subtended angle of a plume when viewed obliquely are described in the accompanying paper.[3]

COLOR DIFFERENCE PERCEPTION THRESHOLD

The color difference perception threshold in the original EPA guidance[1] was based on perception thresholds derived from observations of two samples, each with a uniform color, placed next to each other. The transition between the two colors was a step function. These observations were used to develop a uniform color space called CIE LAB. It was a goal to design this color space so a change of one unit is just perceptible. As described in the Appendix, PLUVUE II uses the CIE LAB equations to calculate the change in color ΔE LAB (called ΔE in this paper), caused by introducing the plume into the sight path. Both the original EPA guidance[1] and the current FLAG guidance[7] use $\Delta E = 1$ as the threshold for the visual perception of a plume of any apparent width.

In the real world, plumes do not have a sharp transition between two areas of uniform color. Also, plumes can subtend a wide angle, so color changes occur gradually over a wide angle. An effort was made to find experimental data for the perception threshold for color differences when the color change takes place smoothly instead of at step function. Experts familiar with the current status of research on human vision were contacted in an effort to locate experimental data for cases where the transition from one color to the other was smooth and could occur over a subtended angle as large as 20 degrees or more. No such data were located. Therefore a Plume Color Demonstration Program (PCDP) was written to generate computer displays simulating Gaussian and square profile plumes with subtended angles (widths on the computer monitor) selected by the user. This program can generate any background color a computer monitor is capable of producing and the contrast and color difference of the plume can be selected by the user.

The use of CRT displays to explore and demonstrate visual effects and to determine perception thresholds is well established. Many perception threshold experiments reported in the literature used a CRT to generate the patterns used in the experiments, including those of Howell and Hess[6] discussed above. The NPS has long used CRT displays to show the effects of haze on scenes and to evaluate and demonstrate haze perception thresholds based on the deciview haze index.

The color of each pixel on a CRT is controlled by three integers between 0 to 255 that control the excitation of the red, green, and blue phosphors. Any color that the monitor can display can be specified by these three numbers. If the monitor is calibrated as described in the Appendix, the display appears gray when these three numbers are equal to each other for each pixel. The use of flat-screen LCD monitors is not recommended for perception experiments because they have artifacts, such as a dependence on the angle of view, that prevent obtaining quantitative results.

The PCDP developed for this project and procedures for its use are described in the Appendix. The user is able to select any background color and superimpose either a square- or Gaussian-profile "plume" of any width on the background. The user can select the color difference between the plume centerline and the background as well as a vertical or horizontal orientation of the plume. Rough experiments, which were not carefully controlled, with gray Gaussian and square wave plumes gave results consistent with the contrast perception thresholds presented above.

To facilitate adjustment of the color difference of a plume, the color difference between the plume centerline and the background is controlled by a scale factor and the difference δ in the R, G, and B values when the scale factor is equal to one. Thus, the integer representing red in the plume centerline differs from the integer for the background by the integer obtained by rounding δR times the scale factor to the nearest integer. The δR and the scale factor can each be either positive or negative. The selection of the δR, δG, and δB values permits the user to select the direction in color space for the color differences generated by adjusting the scale factor. The scale factor is used to control the magnitude of the color differences along the chosen line in color space.

Several types of experiments can be performed once the background RGB values and the δR, δG, and δB values have been selected. One is to select a plume width in pixels and the Gaussian plume profile. Then increase the scale factor from zero until the plume is first perceptible. If desired, the scale factor can be adjusted up and down to find the threshold. Then the background RGB values and the difference in the RGB values can be entered into a spreadsheet based on the equations in the Appendix to determine the corresponding contrast and color difference. It is useful to have this spreadsheet also calculate the subtended angle of the pattern from the pattern width in pixels, the size of a pixel on the CRT, and the distance of the observer from the CRT. Perception experiments were performed using the PCDP for a variety of background and plume centerline colors.

The PCDP can be used to establish a key point – for either a gray or a colored plumes wider than about 100 pixels at the normal viewing distance, the perception threshold for Gaussian plumes is greater than for square plumes. (A simulated plume 100 pixels wide viewed at a distance of two feet subtends an angle of 2.6 degrees on monitors with 0.28 mm per pixel). When the scale factor that determines the contrast or color difference is set so the Gaussian plume is faintly perceptible, or even just imperceptible, changing to a square plume produces an easily perceptible pattern. The perception threshold for color differences in the FLAG guidance is based on experimental conditions like those for the square plume. The Gaussian plumes more closely represent the conditions simulated by PLUVUE II. This result is quite robust, and persists regardless of the colors surrounding the CRT display, the accommodation of the eye, the brightness and contrast settings of the monitor, etc. Clearly, an upward adjustment of the color difference perception threshold in the FLAG guidance is needed for plumes that subtend an angle greater than about one degree.

Determining the exact color difference perception thresholds for Gaussian plumes that subtend wide angles would be a significant undertaking. For each combination of background color, visual surround, accommodation of the eye, plume width, and direction in color space of the color difference, it would be necessary to perform a series of experiments in which only the magnitude of the color difference is changed. Observers would be asked whether or not they could see the plume. Repeating this test many times would generate an “S” shaped curve for the percent of the times the plume was perceived as a function of the color difference. The perception threshold can be set at the color difference that is correctly perceived in 50% of the observations. Repeating such experiments for a range of parameters was beyond the scope of this project.

It is difficult in informal experiments to control the color of the area surrounding the colored display of the PCDP. In some experiments, a square hole was cut in a 60 by 75 cm light blue poster board and it was fastened to the monitor so only the colored area of the PCDP could be seen. Then the background RGB values and the illumination of the poster board were selected so the two colors approximately matched. The results from these observations were similar to those with a less well controlled visual surround.

A limited number of experiments was performed for Gaussian plumes, and one sample of the results is presented in Figure 3. The results reported here were obtained using RGB values for the background of 50, 100, and 200, which produce a background color similar to a blue sky on a clear day. These experiments used the δR, δG, and δB values of 2, 2, and -8. These values make the plume more red, more green, and less blue than the background, so the plume appears more yellow than the background. When the scale factor is equal to one, the color difference is approximately 6.7 while the contrast is 0.0005, or 0.05%. These values make it possible to adjust the plume color in the blue-yellow direction by changing the scale factor while causing very little change in the plume contrast.

Each point in Figure 3 represents a single observation using the settings just described. An open circle indicates the Gaussian plume was not perceptible and a solid black circle indicates the plume was perceptible. The diamonds represent color differences approximately at the perception threshold. The standard procedure of setting the perception threshold at a value that is correctly perceived 50% of the time in a controlled environment indicates that the plume pattern will sometimes be correctly perceived at a contrast or color difference below the perception threshold. Thus, one or a few correct perceptions of a plume pattern when the color difference is less than the candidate perception threshold does not invalidate the candidate threshold.

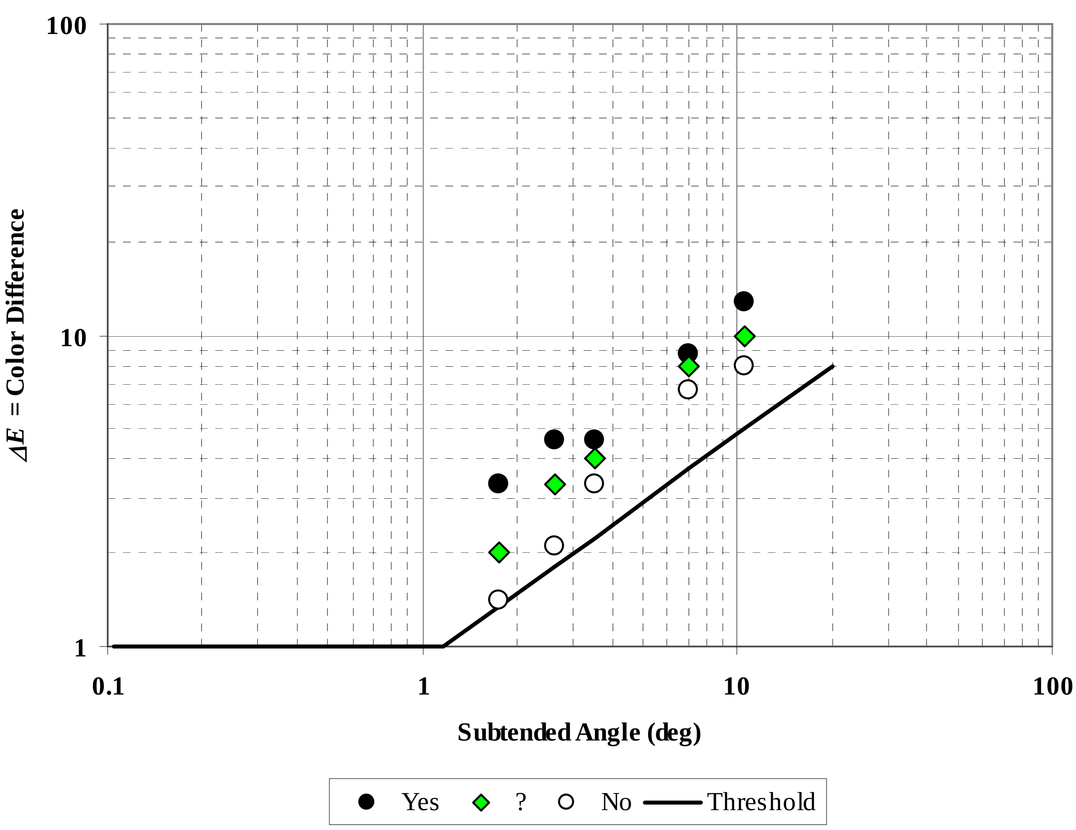
The experimental data in Figure 3 support using a color difference perception threshold shown by the line in Figure 3 in regulatory analyses. For plume subtended angles less than 1.16 degrees, the line has the value ΔE = 1.0, which is the same as the FLAG guidance.[7] For larger subtended angles, the color difference perception threshold is given by Equation 3:

$$\Delta E = 0.896(\phi)^{0.7307} \qquad \text{for } \phi \geq 1.16 \text{ deg} \qquad (3)$$

The data in Figure 3 indicate that the color difference perception threshold in Equation 3 is conservative, i.e., is lower than the observed color difference thresholds.

The line in Figure 3 and Equation 3 were chosen as the color difference perception threshold early in this work when the cross-hatched line in Figure 1 was under consideration for the contrast perception threshold. The line in Figure 3 and Equation 3 were obtained by multiplying the two cross-hatched lines in Figure 1 by a factor of 50. The color difference perception threshold was not changed when the more refined contrast perception threshold described above was adopted.

Figure 3: Data for the dependence of the color difference perception threshold on the apparent width of the plume.



OBSERVATIONS IN THE REAL WORLD

In the real world, plumes are viewed against a background of sky or terrain that does not have a uniform luminance and color, even when there are no clouds. For faint plumes, the effect of a plume is to introduce a small distortion in the luminance and color profile of the background. As the angle subtended by a plume increases (i.e., the plume fills a larger portion of the observers total field of view), the plume is spread over a larger change in the luminance and color of the background sky. For a given value of the plume contrast or color difference, the changes in luminance and color attributable to the plume become a smaller fraction of the naturally occurring variations in the luminance and color of the background sky. Thus, it is reasonable to believe that the adjustment needed to convert laboratory contrast thresholds into thresholds appropriate for the real world increases as the plume subtended angle increases.

The perception thresholds recommended above contain no allowance for the difference between controlled conditions in the laboratory where observers know in advance the pattern to be perceived and the real world where such information is not available. They also make no allowance for the fact that backgrounds in the laboratory are uniform while backgrounds in the real world are not uniform. Therefore, the recommended perception thresholds are conservative.

CONCLUSIONS

Human visual perception thresholds for contrast and color difference are derived for use in regulatory analyses that assess whether or not a point-source plume is perceptible in a Class I area. These thresholds account for the apparent width of the plume, which is the angle subtended by the plume. The contrast perception threshold is based on the same observations as used to establish the original EPA guidance[1] and is give by Equations 1 and 2. The color difference perception threshold is based on new observations and is given by Equation 3.

APPENDIX

Introduction

This Appendix describes the development and use of the Plume Color Demonstration Program (PCDP). Readers can use the color difference perception thresholds presented above to assess plume visibility without studying the information presented here. The information in this Appendix is intended for readers who wish to understand the experimental details and underlying equations, or for readers who may wish to perform additional color difference perception experiments to extend the range of the available data.

Background

The calculations in this Appendix depend on the CIE standard observer, which was defined in 1931. The equations and conventions adopted at that time made it possible to calculate from spectral measurements whether or not two colors appear to match. Those equations and conventions also provide the basis for the calculation in PLUVUE II of parameters characterizing the perceptibility of plumes.

Color vision is three dimensional, linear, and additive. The fact that color vision is three dimensional allows the use of only three phosphors, red, green, and blue, to generate all the colors a computer monitor can display. Any color can be specified by three numbers, the CIE X, Y, and Z.

In principle, a calibrated computer monitor can exactly match the color of the background sky or terrain and the plume viewed against the sky or terrain – as long as those colors fall within the gamut of colors the monitor can generate. However, the perceptions when viewing a monitor are affected by many things. The accommodation of the eye and the colors surrounding the monitor screen have a large effect. The eyes of a person in a room with few windows and a door to the outside are accommodated to the low light level in the room and can see the furnishings quite well. The eyes of a person outside on a sunny day are accommodated to much brighter conditions and see little more than darkness when looking through an open door into the room. A gray area surrounded by black seems lighter than the same gray area surrounded by white. A white projection screen appears to be white when the projector is turned off. If a slide of black lettering on a white background is projected, the lettering appears to be a deep black, even though more light falls on the screen within the letters than when the projector was turned off. Thus, caution is needed in the interpretation of computer displays.

Plume Color Demonstration Program

The PCDP was written in the fall of 2005 in the Visual Basic programming language using the Microsoft Visual Studio .NET 2003 software development platform. It is designed to run under the Microsoft Windows 98 (or later) operating system with the Microsoft .Net Framework version 1.1 (or later) installed. A color monitor with a resolution of 1024 by 768 or better is required. The display area of the PCDP is 600 pixels square.

The PCDP specifies the intensity of the red, green, and blue phosphors for each pixel on the CRT screen on a scale of 0 to 255 for each phosphor. The algebraic symbols R, G, and B represent the values of these integers. The user of the PCDP can directly input the RGB values for the background. The color difference between the plume centerline and the background is controlled by a scale factor and the difference δ in the R, G, and B values when the scale factor is equal to one. Thus, the integer representing red in the plume centerline differs from the integer for the background by the integer obtained by rounding δR times the scale factor to the nearest integer. Each of these variables can be either positive or negative. The selection of the δR, δG, and δB values permits the user to select the direction in color space for the color differences generated by adjusting the scale factor. The program does not allow RGB values calculated from the background plus the scaled differences outside the range 0 to 255, even momentarily.

The program allows generating either square or Gaussian plumes with a width of 1 to 600 pixels. The program does not allow entries outside this range, even momentarily. The width of a Gaussian plume is four times sigma, or two sigma on each side of the centerline. For Gaussian plumes, the RGB values are calculated from a Gaussian profile using floating point arithmetic and then rounded to integers. The axis of the plumes can be either vertical or horizontal.

It was found that under some conditions, integer steps in one or more of the RGB values produce a perceptible change. Under these conditions, the Gaussian pattern appears to be composed of steps instead of a smooth change in brightness. The visual illusion known as Mach bands accentuates the perceptibility of these steps. The website

http://wisebytes.net/illusions/machbands.php

shows an example of Mach bands. Other examples can be found by an Internet search. This problem was addressed by using a checkerboard pattern to simulate half-integer steps in the RGB values. At normal viewing distances, the integer steps in brightness become imperceptible for individual pixels because they subtend a small angle, and the checkerboard pattern has a brightness half way between the brightness of the two integer values used to generate the checkerboard. This refinement of the PCDP significantly decreased the interfering effects of Mach bands in the Gaussian profile patterns.

Calibration of the Computer Monitor

It is necessary to calibrate the CRT monitor to obtain quantitative data. This involves setting the contrast and brightness controls on the monitor, determining the gamma (defined below) for the monitor, and determining the CIE coordinates for each of the three phosphors at full brightness. The procedures below apply to a Sony Trinitron monitor, which was sold by a number of vendors of computer systems.

The contrast control determines maximum brightness of the display, and should be set to the highest available value. The effect of this control can be viewed when the background values in the PCDP are all set to 255. The brightness control should be set to the highest value for which a black screen is black. This setting produces a black screen when the inputs are zero and a perceptibly brighter screen when the RGB inputs are increased by one or two units.

The relation between the RGB inputs to the CRT monitor and the amount of light emitted by the monitor is nonlinear. This relation can be represented by an exponential function with an exponent called gamma. It is necessary to know the gamma of the CRT monitor in order to calculate the CIE coordinates of a displayed color from the RGB input values. Test patterns for determining the gamma of a monitor are available on the Internet at

http://www.aim-dtp.net/aim/evaluation/gamma_space/index.htm.

To find the gamma for your monitor, click on possible values on the left side bar until one is found that causes the two large rectangles to shade from light at the top to dark at the bottom with no differences or colors side to side. The monitor should be viewed from a distance of several feet or more, so the fine-grained patterns in these bars is not perceptible.

The purpose of the two small black bars at the right is to confirm the brightness setting of the monitor. For a correctly set monitor, an alternating pattern of black and dark gray squares will be perceptible in the top bar but not in the bottom bar. Varying the brightness setting can display both these patterns or make both disappear.

These patterns for the determination of the gamma of a CRT monitor clearly illustrate the difficulty of accurate color displays on a flat-screen LCD monitor. The appearance of the patterns changes dramatically with the angle at which the LCD screen is viewed, and no value of gamma makes the bars appear to be uniform shades of gray.

Calculation of CIE Coordinates

This section describes the methods used to calculate the CIE coordinates of the background and also the coordinates of the background at the plume centerline as modified by the plume. The inputs to these calculations are the RGB values used in the PCDP and the outputs are the CIE X, Y, and Z values. The methods and equations used for these calculations were obtained from the website

http://www.dcs.ed.ac.uk/home/mxr/gfx/faqs/colorconv.faq

Normalization of the RGB Values. The RGB values used by the PCDP are integers on a scale from 0 to 255. The first step in the calculation is to divide them by 255 to obtain normalized floating point numbers on a scale of zero to one.

Gamma Correction of the RGB Values. The RGB values are then adjusted for the gain, offset, and gamma of the graphics card and monitor using the equations

$$R' = gain\ R^{gamma} + offset$$

$$G' = gain\ G^{gamma} + offset \qquad (4)$$

$$B' = gain\ B^{gamma} + offset$$

where the values of the gain and offset are determined in part by the brightness and contrast settings of the monitor. The values used were

$$gain = 1$$

$$gamma = 2.5 \qquad (5)$$

$$offset = 0.001$$

The resulting R', G', and B' values are again normalized to a scale of zero to one by dividing them by the gain plus the offset. These calculations are described in Section 2 of the website.

Calculation of the CIE XYZ coordinates. The CIE coordinates of the color generated by the normalized R', G', and B' values are calculated from the CIE coordinates of each of the phosphors. Data for the phosphors in a Trinitron monitor were found at

http://www.uni-mannheim.de/fakul/psycho/irtel/pxlab/doc/manual/ColorCalibration.html.

Converting these data from the CIE Yxy notation to the CIE XYZ notation gave the values in Table A-1 for the CIE coordinates of the three phosphors of a Trinitron monitor at maximum luminance.

Table A-1. CIE coordinates of Trinitron phosphors at maximum luminance.

	Red Phosphor	Green Phosphor	Blue Phosphor
CIE X	38.83	33.16	16.38
CIE Y	21.26	71.52	7.22
CIE Z	2.44	13.34	84.16

Equations 6 convert the normalized R', G', and B' values into the corresponding normalized CIE X, Y, and Z values. The resulting values are normalized on a scale from zero to one.

$$X = 0.3883\ R' + 0.3316\ G' + 0.1638\ B'$$

$$Y = 0.2126\ R' + 0.7152\ G' + 0.0722\ B' \qquad (6)$$

$$Z = 0.0244\ R' + 0.1334\ G' + 0.8416\ B'$$

As described above, the PLUVUE II model calculates the values of these CIE coordinates for the background sky and the background terrain with no plume present and then calculates them again with the centerline of the plume in the sight path.

Calculation of the CIE LAB coordinates. The CIE color space is perceptually non-uniform. The change in the values of the X, Y, and Z coordinates required to produce a perceptible change in color varies greatly depending on the location in the CIE color space. The CIE LAB color space was designed to be more nearly perceptually uniform. The PLUVUE II model calculates the CIE LAB coordinates from the CIE coordinates using the same equations as those presented below.

It is typically the case that the lightest and brightest element in a scene is perceived as white, and then other colors in a scene are perceived in reference to that white. It is this property of human vision that makes it possible during a brilliant yellow-red sunset to perceive a white picket fence as white, even though a photograph of the fence shows it to be quite yellow. PLUVUE II accounts for this property of vision by calculating the CIE coordinates of a "white card," which has a 100% reflectance and is illuminated by the sun and the sky. Here, the CIE coordinates of the white card are indicated by the subscript w. The values in Equations 7 were calculated from Equations 6 for the white screen on a Trinitron computer monitor with each of the RGB values equal to 255.

$$X_w = 0.8837$$

$$Y_w = 1.000 \qquad (7)$$

$$Z_w = 0.9994$$

The CIE LAB coordinates are then calculated using the equations

$$L^* = 116\left(\frac{Y}{Y_w}\right)^t - 16$$

$$a^* = 500\left[\left(\frac{X}{X_w}\right)^t - \left(\frac{Y}{Y_w}\right)^t\right] \quad (8)$$

$$b^* = 200\left[\left(\frac{Y}{Y_w}\right)^t - \left(\frac{Z}{Z_w}\right)^t\right]$$

where the exponent t = 1/3 and L* is normalized on a scale from zero to 100.

These equations are valid when X/X_w, Y/Y_w, and Z/Z_w are greater than 0.008856. PLUVUE II assumes this is always the case and uses these equations. There are alternate equations that should be used for smaller X, Y, and Z values.

Equations 8 appear in Section 4.5 of the website cited above and on Page B-14 of Appendix B of the EPA Workbook for plume visual impact screening and analysis.[1] In both of those sources, the equations contain typographical errors.

Calculation of Perception Parameters

To this point, the calculations are performed separately for the background RGB values used in the PCDP and then for the RGB values in the plume centerline, which are the background values plus the scaled difference values. PLUVUE II also calculates the L*, a*, and b* values separately for the background and then for the background modified by the plume. The plume contrast C and color difference ΔE parameters are calculated from the equations

$$C = (L^*_{plume} - L^*_{background})/L^*_{background} \quad (9)$$

$$\Delta E = \Delta E\ LAB = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2} \quad (10)$$

where Δ indicates the difference between the values calculated with and without the plume present. In words, the color difference is the square root of the sum of the squares of the differences in the three CIE LAB parameters. The contrast is the difference between the brightness with and without the plume divided by the brightness without the plume. The L* parameter is used as a measure of brightness.

For gray plumes against a gray background, Δa*and Δb* equal zero, so the color difference is equal to ΔL*. In this case, the color difference differs from the contrast in that ΔL* is not divided by $L^*_{background}$. When $L^*_{background} = 50$, Equations 9 and 10 indicate that ΔE=1 when C = 0.02. These are the perception thresholds recommended in the FLAG guidance.[7] This agreement of both perception parameters with the FLAG guidance is not possible for other values of $L^*_{background}$ for gray plumes against a gray background.

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KEY WORDS

Visibility, Class I area, modeling, PLUVUE II, contrast, color difference, perception thresholds.

Appendix C

Zell et al. paper on “Effects of Plume Subtended Angle on Visibility Impairment over a Class I Area"

Effects of Plume Subtended Angle on Visibility Impairment over a Class I Area

Paper No. 277

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ABSTRACT

Permitting of a major proposed new or modified emissions source near a Class I area may require the assessment of potential plume visibility impairment within the Class I area. In certain cases, this assessment requires refined analysis using the PLUVUE II plume visibility model. This model calculates the contrast and color difference of a plume against its background, for input date, and time of day, and hourly weather conditions.

In December 2000, the Federal Land Managers' Air Quality Related Values Work Group (FLAG) adopted fixed visibility guideline thresholds for contrast (0.02) and color difference (1.0), based on narrow plumes to which the human eye is most sensitive. However, the original 1978 research showed that contrast perception threshold increased significantly as a function of the angle subtended by the plume (wider, more diffuse plumes are harder to see). Recent research by Willard Richards, *et al.* has demonstrated a similar trend for the color difference perception threshold.

The visibility impairment from a wide plume passing near the observer (which subtends a large angle) is correctly evaluated by comparing the calculated contrast and color difference to thresholds that account for the angle subtended by the plume. This paper describes procedures for calculating subtended angles, and the commensurate improved contrast and color difference thresholds, from information available in PLUVUE, including for lines of sight oblique to the plume. These calculation methods were incorporated into a post-processor, which compares contrast and color difference from PLUVUE with improved thresholds for many PLUVUE output files.

A detailed analysis for multiple observer locations over a five-year period for a specific emission source and Class I area showed that the actual frequency of visibility impairment (exceeding thresholds that account for subtended angle) is much less than that calculated using the conservative FLAG guideline thresholds.

INTRODUCTION

Visibility Impairment Analysis

The Clean Air Act Amendments require that new or modified major sources of emission of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and/or particulate matter (PM) evaluate the effects of plumes on visibility in nearby Class I areas. Permit applications are reviewed for visibility impairment by the Federal Land Managers (FLM) for the Class I area.

The Environmental Protection Agency (EPA) has prescribed a methodology for the assessment of visibility impairment impacts[1], consisting of three levels of analysis arranged in increasing order of detail and refinement. If a simplistic analysis using conservative assumptions demonstrates insignificant impacts below screening threshold values, the more complex analysis need not be performed.

This paper describes the visibility impairment modeling recently performed for an emission source proposed to be located about 24 km from the closest boundary of a National Park. An initial assessment indicated that screening analysis would not be adequate, and that a Level 3 detailed analysis using the PLUVUE II model would be required.

The PLUVUE II model uses a Gaussian dispersion model to calculate hourly-average downwind concentrations, then calculates the contrast and color difference due to the plume relative to the background for lines of sight from an input observer location to up to 16 points along the downwind axis. It takes into account the apparent position of the sun, (which depends on season and time of day), and the distance from the observer to the background, in order to ensure that the plume is not hidden from the observer by a background object. Typically, this analysis is performed for every daylight hour over a five-year period for which the wind blows the plume centerline over the Class I area.

Levels of Concern for PLUVUE II Analysis

The Federal Land Managers' Air Quality Related Values Workgroup (FLAG)[2] has set Levels of Concern for two measures of visibility impairment due to a pollutant plume:

- Plume Contrast: A measure of the relative brightness (positive) or darkness (negative) of a plume as compared to its background. Since both negative and positive values can occur, the Level of Concern was set for the absolute value of the contrast at $|C| < 0.02$.

- Color Difference (ΔE): A measure of the color of the plume relative to its background, calculated over the entire visible spectrum, for which the Level of Concern was set to $\Delta E < 1.0$.

Perception Thresholds and Plume Subtended Angle

Perception research by Howell and Hess (1978)[3] showed that the human eye is most sensitive to contrast between a plume and the background for plumes whose apparent width (angle subtended by the plume relative to the observer) ranges from 0.2 to 1.0 degree. The contrast which is required to be perceived by the human eye for wider plumes increases rapidly for larger subtended angles.[3]

Similarly, Willard Richards, *et al*[4] have demonstrated that the threshold at which the human eye can detect color difference (ΔE) also increases rapidly as a function of the plume subtended angle, for angles larger than about one degree.

The Levels of Concern for contrast and color difference established in the Federal Land Managers' Air Quality Related Values Workgroup (FLAG) document[2] are near the minima of the perception curves, which occur at small subtended angles where the human eye is most sensitive to contrast and color difference.

Modeling experience has shown that the highest contrast and color differences calculated by PLUVUE II occur when the plume centerline passes relatively close to an observer in the Class I area. A plume emitted from a source tens of kilometers away can be hundreds of meters wide at the observer's line of sight, and therefore can subtend an angle much larger than 1 degree. A wide plume may not actually be visible to the observer, even if its contrast or color difference exceeds the low FLAG thresholds[2] which apply to narrow plumes.

In some cases, where the plume centerline passes extremely close to the observer location, the observer may be inside the plume, and therefore unable view the background used in the PLUVUE II calculations.

Purpose of This Paper

This paper investigates the effect of comparing contrast and color difference values calculated by PLUVUE II to perception thresholds which vary as a function of subtended angle, which are more indicative of the observer's actual ability to perceive the plume than a fixed threshold based on a narrow plume. Equations are presented for the variation of contrast and color difference perception thresholds as a function of subtended angle, based on the perception research performed by Howell and Hess[3] and Richards, *et al.*[4].

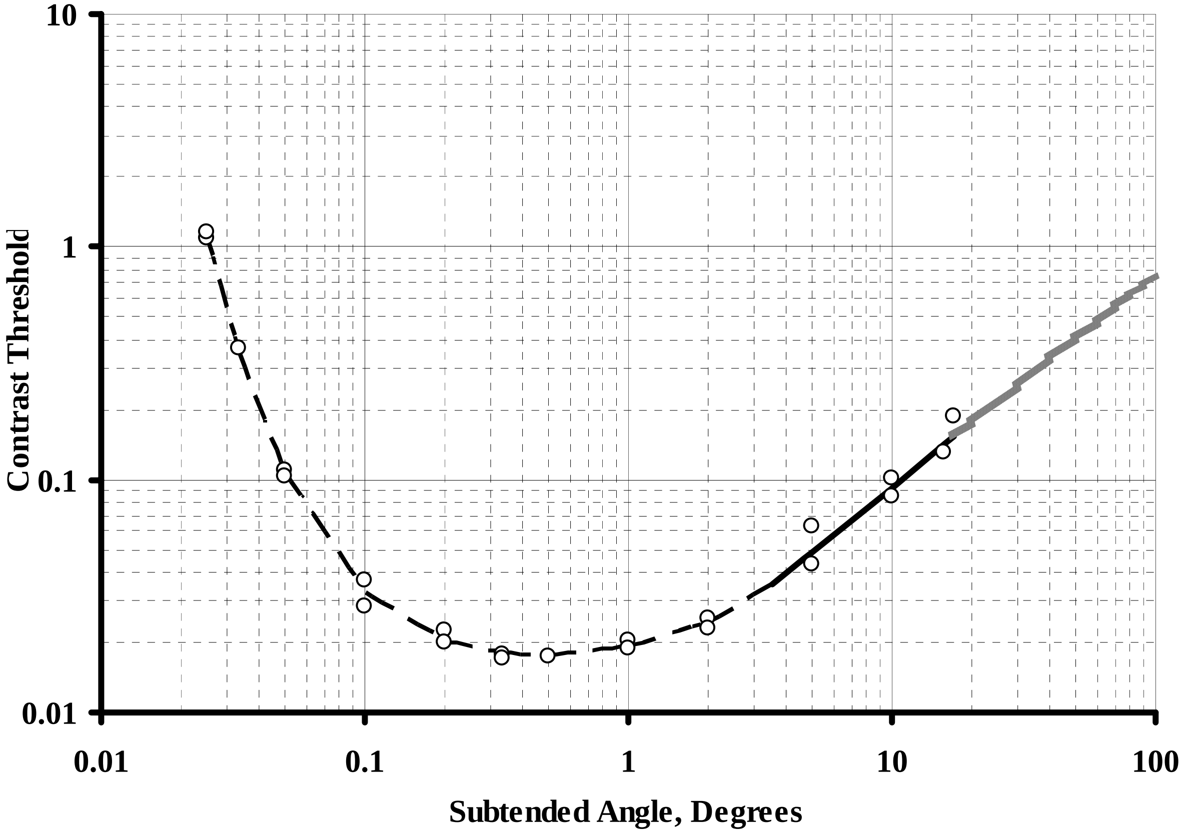
A method is presented to calculate the angle subtended by a plume as a function of source and observer location, downwind distance along a plume centerline, and plume parameters calculated by the PLUVUE II program. This method was incorporated into post-processing software used to summarize and evaluate the results from large numbers of PLUVUE II output files. This software was used to compare the frequency with which contrast and color difference calculated by PLUVUE II exceed variable perception thresholds as functions of subtended angle, with the frequency of exceeding fixed (FLAG) Levels of Concern.

EXPERIMENTAL METHODS

Contrast Threshold and Subtended Angle

Figure 1 below presents a log-log graph of the contrast perception thresholds derived from measurements by E. R. Howell and R. F. Hess (1978)[3] as a function of the angle subtended by the plume, in degrees. The EPA guidance[1] for contrast perception thresholds was based on Howell and Hess' observations[3] of five-cycle sine-wave patterns. They report that the perception thresholds for two observers were higher when viewing a one-cycle sine-wave pattern, which is more representative of a Gaussian plume profile.[4] When this correction is applied to the contrast thresholds measured for five-cycle sine-wave patterns[3], the results are shown by the open circles on Figure 1.

Figure 1: Contrast Threshold as a Function of Subtended Angle (Howell and Hess, 1978)



The Level of Concern for contrast recommended in the FLAG document[2] ($|C| < 0.02$) corresponds to the lowest thresholds measured for subtended angles between 0.2 and 1.0 degree. However, for subtended angles greater than 1 degree, representative of the wide plumes passing close to an observer in a Class I area, the minimum contrast at which the observer can perceive the plume increases with subtended angle.

At the largest subtended angle for which measurements were made by Howell and Hess[2] (17.24°), the contrast threshold is nearly an order of magnitude higher than the FLAG Level of Concern[1].

The dashed line in Figure 1 represents a fourth-order polynomial regression of the logarithm of contrast threshold as a function of the logarithm of subtended angle, for the experimental values at angles up to (and including) 5.0 degrees:

$$\log C_t = -1.713 + 0.207(\log\phi) + 0.310(\log\phi)^2 + 0.183(\log\phi)^3 + 0.311(\log\phi)^4 \quad \text{(Eq. 1)}$$

where the symbol “log” represents a logarithm to the base ten (10), and:

C_t = contrast perception threshold

ϕ = angle subtended by plume, degrees

For subtended angles less than 5 degrees, Equation 1 fits the Howell and Hess[3] data with a root-mean-square (RMS) error of 8.6%, but it tends to over-estimate contrast thresholds at higher angles. Since all coefficients in Equation 1 are positive, extrapolation beyond the range of the data might result in unrealistically high predicted contrast thresholds.

A more reasonable extrapolation of the Howell and Hess[3] data to subtended angles above the range of measurement was obtained by performing a linear regression (in log-log coordinates) on the last six data points (from 5° to 17.24° inclusive):

$$\log C_t = -1.950 + 0.917(\log\phi) \quad \text{(Eq. 2)}$$

This line crosses Equation 1 at $\phi = 2.61^\circ$ and $\phi = 4.67^\circ$, but the slope of Equation 1 does not match the slope of Equation 2 at these points. In order to ensure a smooth transition between the two regressions, the angle was found at which the slopes of the two curves were equal.

Differentiating Equation 1 with respect to $(\log\phi)$, setting the result equal to 0.917 (the slope of Equation 2), and solving for ϕ results in equal slopes at $\phi = 3.53^\circ$. The intercept of the straight line (Equation 2) was then adjusted so that the calculated contrast thresholds were equal for the two equations at $\phi = 3.53^\circ$, which resulted in a modified linear regression:

$$\log C_t = -1.932 + 0.917(\log\phi) \quad \text{(Eq. 3)}$$

Equation 3 fits the Howell and Hess data[3] for angles from 5.0 to 17.24 degrees (inclusive) with an RMS error of 14.1%, and is plotted as the solid dark line in Figure 1. The extrapolation of this equation to higher subtended angles is shown by the gray line in Figure 1.

In the post-processing software for PLUVUE II, the improved contrast threshold was calculated using Equation 1 for subtended angles less than 3.53°, and using Equation 3 for subtended angles greater than 3.53°.

Color Difference Threshold and Subtended Angle

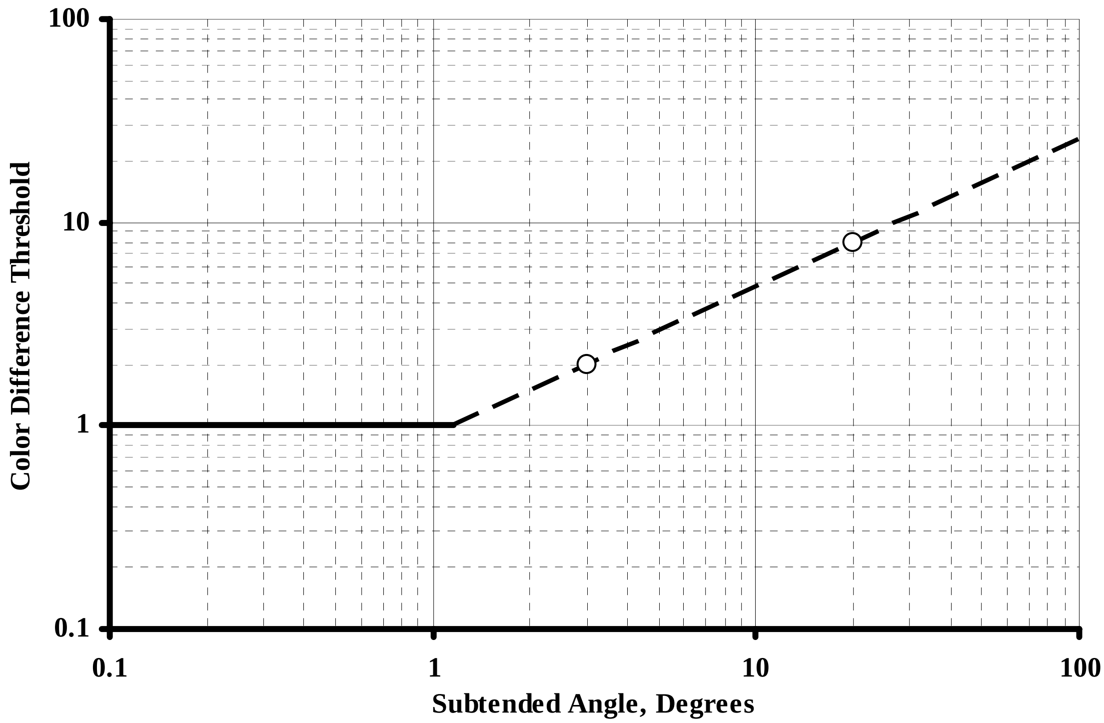
L. Willard Richards, *et al.*[4] investigated the variation of the color difference perception threshold as a function of plume subtended angle. A preliminary theoretical equation was developed by multiplying an earlier regression of the Howell and Hess[3] contrast threshold data appearing in the original EPA guidance[1] by a fixed constant, assuming that color difference and contrast perception thresholds are proportional at all subtended angles.

This theoretical equation predicts a color difference perception threshold of $\Delta E_1 = 2.0$ at a subtended angle of $\phi_1 = 3^\circ$, and $\Delta E_2 = 8.0$ at a subtended angle of $\phi_2 = 20^\circ$. If a straight line is drawn between these two points (open circles on Figure 2) on log-log coordinates, the equation of this line for the color difference threshold ΔE_t is a power-law function:

$$\Delta E_t = 0.896(\phi)^{0.731} \qquad \text{(Eq. 4)}$$

This equation is plotted as the dashed line in Figure 2 below. If ΔE_t is set to 1.0 and Equation 4 is solved for ϕ, it is found that the improved color difference threshold using Equation 4 is equal to the FLAG Level of Concern[1] of $\Delta E_t = 1.0$ for a subtended angle of $\phi = 1.16^\circ$.

Figure 2:
Color Difference Threshold as a Function of Subtended Angle



In the post-processing software for PLUVUE II, the improved color difference threshold was calculated using Equation 4 (dotted line on Figure 2) for subtended angles greater than 1.16^o, and was assumed equal to the FLAG Level of Concern[1] of $\Delta E_t = 1.0$ (solid black line on Figure 2) for subtended angles less than 1.16^o. This correction to the color difference threshold was approved by the National Park Service in the visibility modeling protocol for a proposed emission source near a National Park.

In 2005, Willard Richards *et al*[4] developed a computer application, called the Plume Color Demonstration Program[4], which displayed on a computer monitor the appearance of a Gaussian plume with a given color, intensity, and plume width against a background of a given color. The ratio of the width of the virtual "plume" on the monitor screen to the distance of an observer to the screen can be used to define the angle subtended by the virtual "plume".

Richards, *et al.*[4] used this program to demonstrate that the color difference perception thresholds were significantly higher than those predicted by Equation 4 over a range of subtended angles from 1.75^o to 10.49^o.

However, the more conservative thresholds given by Equation 4 were used for visibility impairment modeling for the proposed emission source, since they had already been approved for use in the modeling protocol by the National Park Service.

PLUVUE II Pre-Processing and Post-Processing Software

Power Plant Permitting Project

This study of the effect of subtended angle on contrast and color difference thresholds in PLUVUE II was part of the process of permitting a proposed power plant, to be located about 23.7 km east-southeast of the closest boundary of a National Park.

A review of the terrain, overlooks, and scenic vistas in the Class I area by the Federal Land Managers resulted in the identification of seven observer locations within the National Park, for which the visibility impacts were to be calculated.

The EPA *Workbook for Plume Visual Impact Screening and Analysis*[1] recommends a minimum "offset" angle of 11.25^o (between the downwind axis and the azimuth from the source to the observer location) as the "worst-case" wind direction to be analyzed. In this case, however, the arc of wind directions which blow over the National Park is only 15^o wide (109^o to 124^o), and application of the 11.25^o minimum offset angle for centrally-located observer locations would eliminate all wind directions from consideration.

For each observer location, the analyses were performed for all daylight hours over a five-year period for which the wind would blow the plume centerline over the Park, with wind directions originally measured to the nearest 10 degrees "randomized" to 1-degree increments.

According to hourly meteorological data for the years 1990 through 1994 (inclusive) obtained from a nearby weather station, there were 901 such hours to be modeled. Modeling for each of seven observer locations required a total of 6,307 executions of the PLUVUE II model.

Automated PLUVUE II Processing Software

Due to the large amount of data to be processed, and the repetitive nature of many of the inputs, an automated method was developed for generating PLUVUE II input files, executing a series of PLUVUE II files batchwise, and summarizing PLUVUE II output in a compact and user-friendly form. Three software applications were developed:

- PLUVUGEN: a program to combine input data from various input files, generate PLUVUE II input files, and a batch file that will execute them, for a given observer location and wind direction;

- PLUVUBAT: a program to execute PLUVUE II batchwise according to the batch file generated by PLUVUGEN;

- RDPLUVUE: a post-processor that extracts useful information from PLUVUE II output files, and summarizes the number of hours for which contrast and color difference calculated by PLUVUE II exceeded Levels of Concern thresholds, for a given observer location and wind direction.

The PLUVUGEN Pre-Processor

For a given observer location and wind direction, the PLUVUGEN pre-processor combines data from five input files to generate PLUVUE II input files for all daylight hours in the hourly meteorological data file for which the wind blows from the given direction. The PLUVUGEN pre-processor substitutes the appropriate meteorological data for the selected hours in each PLUVUE II input file.

A common file is used for “default options” for all runs, as well as a common file containing stack and emission data. Another input file contains information specific to the observer location, and another input file contains information specific to a given combination of observer location and wind directions.

This “wind-direction-dependent” input file includes a set of downwind distances from the emission source, which define points the plume centerline. PLUVUE II is coded to calculate contrast and color difference for “lines of sight” from the observer location to each point on the centerline. The downwind distances are chosen so that the azimuths of the lines of sight are close to fixed 15^{o} increments of azimuth at which distances from the observer to the background object are input to PLUVUE II.

The PLUVUGEN pre-processor also calculates inclination angles from the observer to the farthest visible background object along each line of sight.

The RDPLUVUE Post-Processor

For a given observer location and wind direction, the RDPLUVUE post-processor reads the values of contrast and color difference calculated by PLUVUE II for each downwind distance, and prints a one-line summary of the highest values of contrast and color difference for each modeled hour, and whether they exceed the appropriate thresholds.

The RDPLUVUE post-processor excludes some situations from consideration, such as if the plume centerline is behind a background object relative to the observer, or outside the Park boundary. It also prints warning messages of other conditions that might prevent the observer from seeing the plume, such as poor natural visibility due to rain, snow, or fog.

The PLUVUE II model calculates the inclination angle β_i from the observer location to the plume centerline at each downwind distance x_i. If this angle is greater than the inclination angle to the background calculated by PLUVUGEN, the plume can only be viewed against sky background. In this case, the RDPLUVUE program only takes into account contrast and color difference values calculated by PLUVUE II against sky background, not against ground-level (white, gray, or black) backgrounds.

The calculations of subtended angle, and adjustments to contrast and color difference thresholds based on subtended angle, are performed by the RDPLUVUE post-processor, using information output by PLUVUE II for each line of sight. The program also has an option to bypass these calculations and compare the contrast and color differences calculated by PLUVUE directly to the fixed FLAG Levels of Concern.[2]

Calculation of Angle Subtended by Plume

Data Available from PLUVUE II

The PLUVUE II model normally calculates contrast and color difference along up to 16 lines of sight extending from the observer location through the plume. Each line of sight is defined by a line from the observer location through a point on the plume centerline whose distance x_i downwind of the emission source has been input to PLUVUE II.

The PLUVUE II model calculates the orientation of each line of sight relative to the sun position based on the following input information:

X_s = Universal Transverse Mercator (UTM) easting coordinate of stack, m
Y_s = UTM northing coordinate of stack, m
X_o = UTM easting coordinate of observer location, m
Y_o = UTM northing coordinate of observer location, m
z_o = Elevation of observer location above sea level, m
ω = Direction from which wind is blowing, degrees clockwise from north.

The PLUVUE II model contains a Gaussian dispersion model, which calculates the following parameters for each downwind distance x_i:

h_{ci} = height of plume centerline above the ground, m
σ_{yi} = standard deviation of crosswind dispersion, m
σ_{zi} = standard deviation of vertical dispersion, m

Since the PLUVUE II model assumes that the plume centerline follows the terrain, the elevation of the plume centerline z_{ci} above sea level at a downwind distance x_i is:

$$z_{ci} = z_{gi} + h_{ci} \qquad \text{(Eq. 5)}$$

where z_{gi} is the input elevation of the ground above sea level at downwind distance x_i. All the information mentioned above is available to the RDPLUVUE post-processor.

Rotation of Coordinate Axes

In order to simplify the calculations, a wind-based coordinate system is defined whose origin is at sea level directly below the emission source, with the *x* axis extending downwind, and the positive *y* axis to the right when looking downwind. In this coordinate system, the coordinates of a point *C* on the plume centerline at a distance x_i downwind are $(x_i, 0, z_{ci})$. The downwind and crosswind coordinates of the observer location x_o and y_o are obtained from the UTM coordinates *X* and *Y* by rotation of axes as follows:

$$x_o = (X_o - X_s)\sin\omega + (Y_o - Y_s)\cos\omega \qquad \text{(Eq. 6)}$$
$$y_o = (X_o - X_s)\cos\omega - (Y_o - Y_s)\sin\omega \qquad \text{(Eq. 7)}$$

Equivalent Plume Width

In the contrast perception experiments, the plume subtended angle is calculated using the width of one cycle of the sine wave pattern[3]. The best agreement between sine-wave and Gaussian patterns is obtained when the subtended angle for Gaussian plumes is calculated using four times the Gaussian sigma. Thus, the Gaussian plume width is 2σ on each side of the plume centerline.

In a Gaussian dispersion model, at a given downwind distance x_i, the concentration distribution through the plume in a crosswind vertical plane at $x = x_i$ is given by:

$$c(y,z) = c_c \exp\left[\frac{-y^2}{2\sigma_{yi}^2}\right]\exp\left[\frac{-(z - z_{ci})^2}{2\sigma_{zi}^2}\right] \qquad \text{(Eq. 8)}$$

where c_c represents the concentration at the plume centerline.

For an observer at the same elevation and downwind distance as the plume centerline ($z_o = z_{ci}$ and $x_o = x_{ci}$), whose line of sight is perpendicular to the plume centerline, the pollutant concentration at the plume edges $z = z_{ci} \pm 2\sigma_{zi}$ equivalent to the one-cycle sine-wave pattern, from Equation 8, is given by:

$$c(y = 0, z = z_{ci} \pm 2\sigma_{zi}) = c_c \exp(-2) = \frac{c_c}{e^2} \qquad \text{(Eq. 9)}$$

For an observer whose line of sight is oblique to the plume centerline, the apparent plume width is defined by two points on a line through the plume centerline (at the given downwind distance x_i) perpendicular to the line of sight, where the pollutant concentration is c_c / e^2. According to Equation 8, an envelope of constant concentration c_c / e^2 is given by:

$$\frac{y^2}{4\sigma_{yi}^2} + \frac{(z - z_{ci})^2}{4\sigma_{zi}^2} = 1 \qquad \text{(Eq. 10)}$$

which defines an ellipse centered at $(x_i, 0, z_{ci})$, whose crosswind semi-axis is $2\sigma_{yi}$, and whose vertical semi-axis is $2\sigma_{zi}$, in a vertical plane at $x = x_i$. The apparent plume width for the observer is defined by the two points where a line perpendicular to the line of sight in the plane $x = x_i$ crosses the ellipse defined by Equation 10.

This is illustrated in Figure 3 on the next page, where point *C* on the plume centerline is the center of an ellipse in a plane perpendicular to the plume centerline. The line E_1E_2 is perpendicular to the line of sight *OC* from the observer *O* to the plume centerline at point *C*, and crosses the ellipse at points E_1 and E_2.

Angle Subtended by Plume

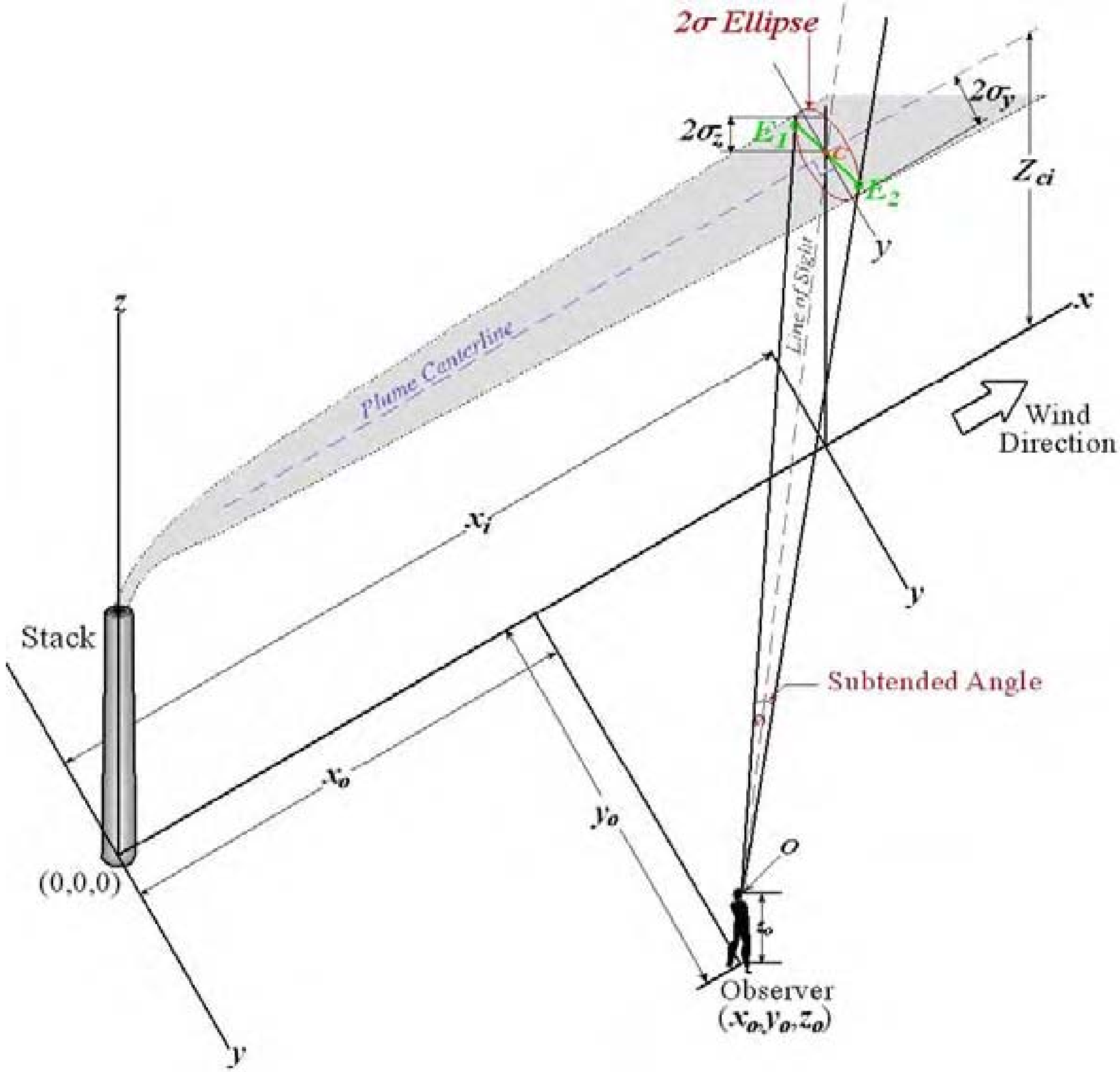
The angle subtended by the plume boundary is calculated by applying the law of cosines to the triangle formed by the observer point *O* and the two boundary points E_1 and E_2 on the ellipse:

$$\cos\phi = \frac{d_{o1}^2 + d_{o2}^2 - d_{12}^2}{2 d_{o1} d_{o2}} \qquad \text{(Eq. 11)}$$

where:

d_{12} = distance from point E_1 to E_2 on the ellipse, m
d_{o1} = distance from observer location to point E_1 on the ellipse, m
d_{o2} = distance from observer location to point E_2 on the ellipse, m

Figure 3: Angle Subtended by Plume



Summary of Calculation Procedure

For a given PLUVUE II output file, the RDPLUVUE post-processor first calculates the downwind and crosswind coordinates of the observer location using Equations 6 and 7. Then, for each downwind distance x_i, the program calculates the angle subtended by the plume as follows:

1) Calculation of coordinates of the points on the ellipse which define the plume width.

2) Calculation of distances between the observer location and each point on the ellipse, and between the two points, from their coordinates.

3) Calculation of the subtended angle using Equation 11.

Once the subtended angle has been calculated, the contrast threshold C_t is calculated using either Equation 1 (if $\phi \leq 3.53^\circ$) or Equation 3 (if $\phi > 3.53^\circ$).

The color difference threshold ΔE_t is calculated using either Equation 4 (if $\phi > 1.16^\circ$), or set to the FLAG Level of Concern[2] (if $\phi \leq 1.16^\circ$).

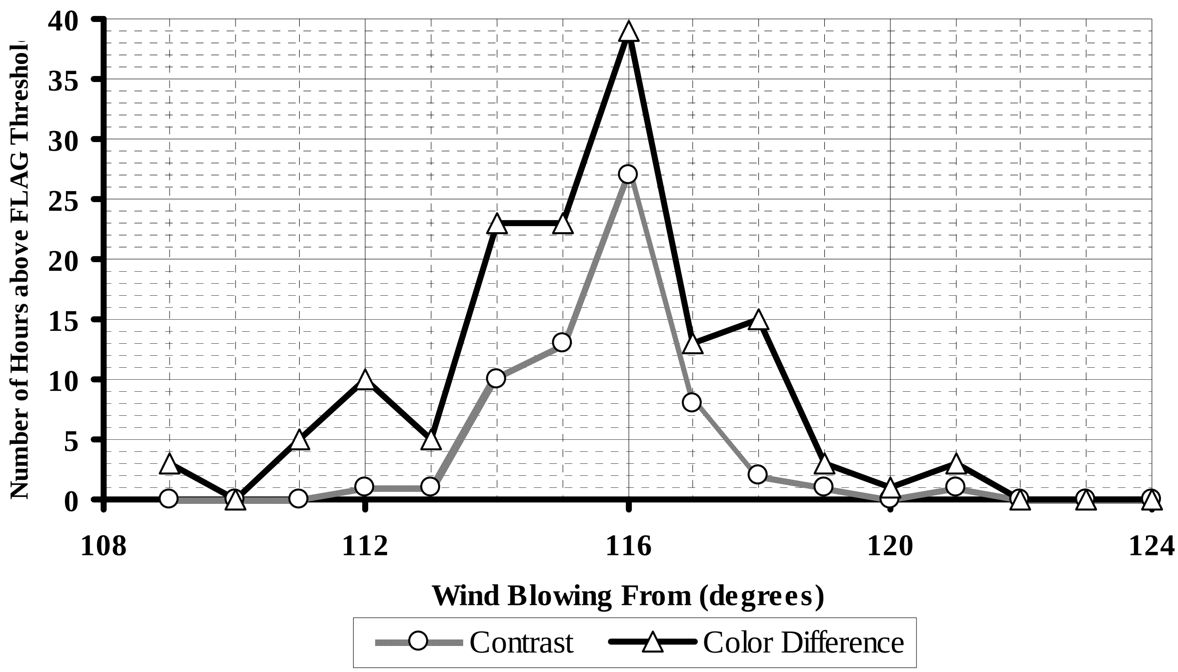
RESULTS AND DISCUSSION

Comparison of PLUVUE Output to FLAG Thresholds

For each of the seven observer locations, the PLUVUE II model was executed for each of the 901 hours for which the wind direction blew the plume centerline over the National Park. The RDPLUVUE post-processor was used to determine the number of hours for which the contrast and color difference calculated by PLUVUE II exceeded either the fixed Federal Land Managers' Air Quality Related Values Workgroup (FLAG) thresholds[2], or thresholds that account for subtended angle as described above.

The number of hours for which contrast and color difference exceeded the fixed FLAG thresholds[2] depended strongly on the wind direction, reaching a peak for the wind direction which blows the plume centerline directly over the observer location. Figure 4 below presents a graph of the number of hours for which the contrast (gray line) and color difference (black line) were greater than the FLAG thresholds for a particular observer location (H), which would be directly downwind of the emission source for a wind blowing from 115.9°.

Figure 4: Number of Hours Above FLAG Thresholds at Observer H as a Function of Wind Direction



This graph clearly shows that the number of hours above the FLAG threshold[2] reaches a maximum when the wind blows the plume nearly directly at the observer location, and decreases rapidly in either direction. Since each wind direction represents a composite sample of many different combinations of dispersion conditions (wind speed, temperature, humidity and stability), it also indicates that the calculated contrast and color differences are highest when the wind blows the plume closest to the observer location.

For this observer location, a wind from 116^{o} blows the plume centerline nearly directly over the observer location, and the observer would be inside the plume, and unable to distinguish it from the background. For winds blowing from 114^{o} through 118^{o} (offset angle $< 2.1^{o}$), a line of sight through a point along the plume centerline either upwind or downwind of the observer travels a long trajectory through the plume, resulting in high values of contrast and color difference. However, the plume would also subtend very large, possibly obtuse ($> 90^{o}$) angles, and the observer would not actually be able to discern such a wide, diffuse plume against the background, according to the graphs in Figure 1 and Figure 2.

Figure 4 shows that there were only three hours above the FLAG thresholds[2] for offset angles greater than 5.1^{o} (outside of the range of wind directions from 111^{o} through 121.2^{o}), which is less than half of the minimum offset of 11.25^{o} recommended by the EPA *Workbook for Plume Visual Impact Screening and Analysis*[1].

It should be noted that the number of hours is higher for plumes passing to the south of the observer (wind directions $< 116^{o}$) than for plumes passing to the north of the observer (wind directions $> 116^{o}$). For plume passing to the south of the observer, a line of sight to the plume centerline would pass closer to the position of the sun (which tends to highlight plume contrast), than for a back-lit plume passing to the north of the observer.

When compared to the fixed FLAG thresholds, trends similar to that shown in Figure 4 were found for six out of seven observer locations, with the maximum number of hours above thresholds occurring for the wind direction which blew the plume closest to each observer location, decreasing rapidly as the offset angle increased in either direction. For the seventh observer location, only one hour exceeded the FLAG threshold, so no trend could be observed.

Comparison of PLUVUE II Output to Improved Thresholds

The comparison of PLUVUE II output to thresholds that account for subtended angle showed that there were only four hours over the entire five-year period during which the calculated contrast or color difference exceeded the improved thresholds at any of the seven observer locations.

Three of these hours occurred during early morning, where the stability class listed in the hourly meteorological data file was E or F (very unfavorable for dispersion), which normally only occur at night. The other hour occurred shortly before sunset, with the sun only 2.2 degrees above the horizon, and sensitivity studies have shown that contrast and color difference values calculated by PLUVUE II can be unrealistically high for sun angles less than 5^{o} above the horizon.

Table 1 below compares the number of hours (over the five-year period) during which the contrast and color difference values calculated by PLUVUE II for the proposed emission source were greater than the fixed FLAG thresholds, or greater than the thresholds that account for the angle subtended by the plume.

Table 1: Number of Hours Above FLAG and Improved Thresholds

Observer Location==>	B	H	M	N	P	R	S
Contrast: Number of Hours >							
FLAG Threshold	35	64	41	61	17	21	0
Threshold Adjusted for Subtended Angle	2	1	2	3	1	1	0
Color Difference: Number of Hours >							
FLAG Threshold	98	143	131	110	30	51	1
Threshold Adjusted for Subtended Angle	2	2	1	2	1	1	0
Number of Hours > Either Threshold							
FLAG Thresholds	100	148	137	118	31	52	1
Thresholds Adjusted for Subtended Angle	2	2	2	3	1	1	0

For the proposed emission source, comparison of PLUVUE II output to the fixed FLAG thresholds (intended for narrow plumes which subtend angles less than 1.16^o) would suggest that visibility impairment would occur during 100 hours or more (over a five-year period) at four of the seven observer locations. However, when the same PLUVUE II results are compared to thresholds which measure the observer's ability to perceive the actual wide plume, visibility impairment would only occur at a maximum of 3 hours at any observer location, only under extreme conditions (night-time stability and/or low sun angle).

The reason for this difference is suggested by Figure 4, where most of the hours above the FLAG thresholds occur for offset angles (between the downwind axis and the line from the source to the observer) less than 3 degrees. At downwind distances of more than 23.7 km (the closest park boundary to the emission source), for daytime stability classes (A, B, C, or D), $\sigma_{yi} \geq 1000m$, and the plume ellipse (Equation 9) for n = 2 is at least 800 m high and 4000 m wide. For offset angles less than 3^o, the observer location is less than 2 km crosswind from the plume centerline, so that the plume subtends large angles. According to Figures 1 and 2, the observer cannot distinguish the wide, diffuse plume from the background, even if the calculated contrast and/or color difference are above the FLAG thresholds.

These results (Figure 4 and Table 1) show that at low offset angles, the plume subtends a large angle at the observer location, and it may not be perceptible by the observer, so that the FLAG thresholds intended for low subtended angles are not applicable.

In Table 1, it should be noted that the number of hours above either threshold were less than the sum of the number of hours of contrast above threshold, and the number of hours of color difference above threshold. There were many hours for which both contrast and color difference exceed the FLAG threshold, and the color difference was more likely to exceed the FLAG threshold than contrast, at all observer locations.

Similarly, there were only four hours during which the contrast or color difference calculated by PLUVUE II exceeded the improved thresholds, although the sum of the number of hours for all observer locations is greater than 4. The same four hours resulted in exceedances of adjusted thresholds at multiple observer points.

CONCLUSIONS

The fixed contrast and color difference thresholds given in the Federal Land Managers' Air Quality Related Values Workgroup (FLAG) document[2] are based on narrow plumes which subtend angles of less than 1.16^{o} at the observer location.

Perception threshold research[3,4] has shown that the thresholds at which the human eye can distinguish contrast and color difference between a plume and the background increase as a function of the angle subtended by the plume. Regression equations are presented for thresholds at which contrast and color difference can be perceived as a function of subtended angle.

Post-processing software has been developed which can calculate the angle subtended by a plume, whose width is defined by a two-sigma ellipse around the plume centerline, relative to a given observer location along a given line of sight. This software can compare contrast and color difference values calculated by PLUVUE II to thresholds that account for subtended angle, using the regression equations described above.

A case study for a proposed emission source to be located 24 km from a National Park shows that the probability of PLUVUE II calculating contrast or color difference values greater than the FLAG thresholds is greatest at low offset angles (where the downwind axis passes close to the observer location).

Under these conditions of low offset angles, the plume subtends large angles relative to the observer location (or the observer is inside the plume), and the observer often cannot distinguish such a wide, diffuse plume from the background, despite the exceedance of the FLAG thresholds intended for narrow plumes.

The EPA *Workbook for Plume Visual Impact Screening and Analysis*[1] recommended a minimum offset angle (between the downwind axis and a line from the emission source to the observer) of 11.25^{o} for visibility impairment analysis. Visibility impairment modeling at lower offset angles leads to an unrealistically high number of exceedances of the FLAG thresholds, because the subtended angles are much larger than those for which the FLAG thresholds were intended.

Adjustment of contrast and color difference thresholds as functions of subtended angle (using appropriate post-processing software) enable a more realistic modeling of visibility impairment at low offset angles, while taking into account the difficulty of the observer to distinguish a wide, diffuse plume from its background, as compared to a narrow, compact plume.

REFERENCES

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KEY WORDS

Visibility, Class I area, modeling, PLUVUE II, contrast, color difference, thresholds, subtended angle.

Appendix D

Site-Specific Adjustment to Land Use for AERSURFACE Modeling

As described in Section 3.4, AERMET was used for the processing of the Dulles International Airport data for the AERMOD modeling. One of the auxiliary steps needed for the meteorological data processing is the determination of appropriate surface characteristics needed by AERMET (surface roughness, Bowen ratio, and albedo) from digit land use data provided as input to the AERSURFACE program.

The current version of AERSURFACE (Version 08009) supports the use of land cover data from the USGS National Land Cover Data 1992 archives (NLCD92). The NLCD92 archive provides data at a spatial resolution of 30 meters based upon a 21-category classification scheme applied over the continental U.S. The AERMOD Implementation Guide recommends that the surface characteristics are determined based on the land use within 1 km from the site where the surface meteorological data were collected. The selection of the land use types assigned in the NLCD92 database will be reviewed and may be altered with justification based upon a site-specific analysis.

As recommended in the AIG for surface roughness, the 1-km radius circular area centered at the meteorological station site can be divided into sectors for the analysis; each chosen sector has a mix of land uses that is different from that of other selected sectors. The land use depiction is shown in Figure D-1 as a aerial photo and in Figure D-2 with digital land use assignments. It is evident from Figure D-2 that the 1-km circle is dominated by the land use category 85 ("urban/recreational grasses"). This type of cover is described[1] as follows:

"Vegetation (primarily grasses) planted in developed settings for recreation, erosion control, or aesthetic purposes. Examples include parks, lawns, golf courses, airport grasses, and industrial site grasses." The very low surface roughness lengths involved indicate that these areas are kept well manicured and mowed, such as a lawn[2] with a height of 2 cm. Our review of Figure D-1 indicated that the area in question was not consistent with this characterization.

Further investigation involved a review of photos of the Dulles airport anemometer site in 8 cardinal directions, provided in Figures D-3 through D-10 for directions looking north clockwise through northwest. It is evident from the photos that the nature of the grassland (with occasional shrubs) is such that the area is not consistent with mowed and manicured lawns, but rather natural grasslands such as those used for grazing. The Randerson reference indicates that for grassy areas with a height of about 50 cm (similar to that in the photographs), the roughness length should be about 10 cm. This value matches that for a more appropriate land use category, which is 71 (grasslands/herbaceous). This change was therefore made to the AERSURFACE run by introducing an IF statement in the FORTRAN code that changed the land use category from 85 to 71 for this application.

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[1] See http://landcover.usgs.gov/classes.php.

[2] The AERSURFACE citation for the grassy area surface roughness values is Table 5.4 in Randerson, D., 1984, "Atmospheric Boundary Layer," in *Atmospheric Science and Power Production*, ed., D. Randerson. Technical Information Center, Office of Science and Technical Information, U.S. Department of Energy, Springfield, VA, 850pp. This table indicates that the surface roughness is about 1/10 of the height of the grass.

Figure D-1 Sectors Used for Surface Characteristics at Dulles International Airport

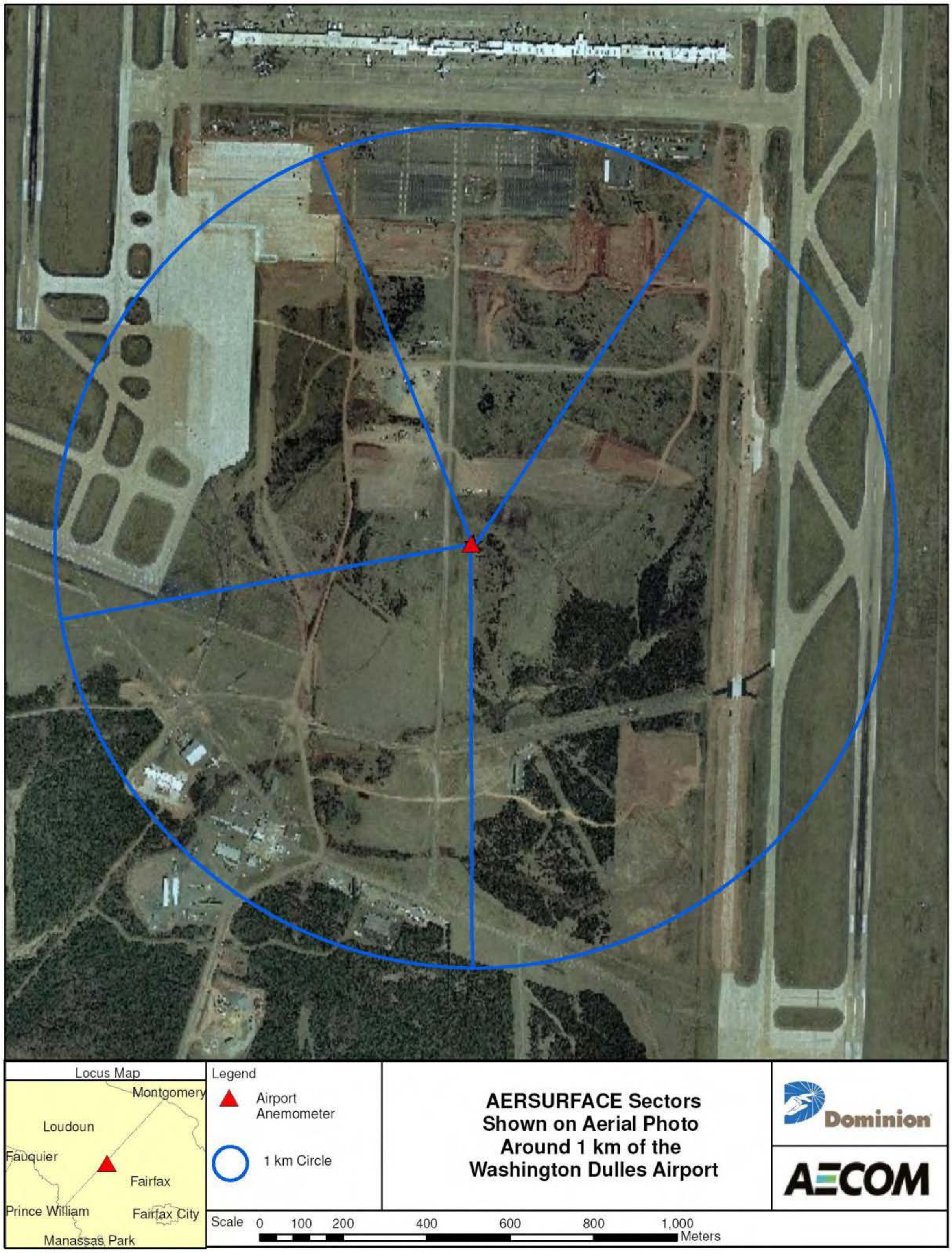

Figure D-2 1-km Radius for Dulles International Airport With Surface Roughness Sectors Shown on Land Use Imagery

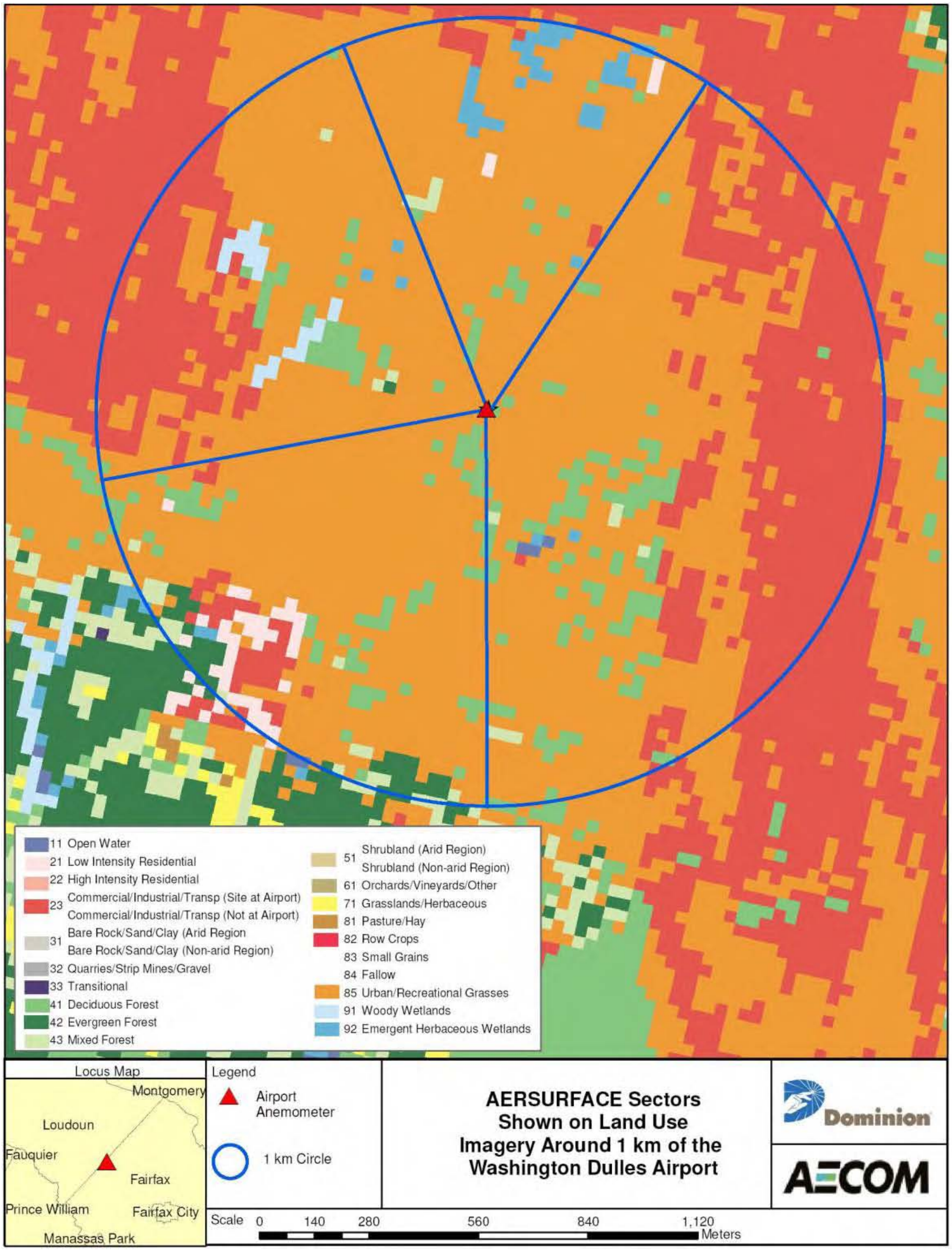

Figure D-3 View of Dulles Meteorological Station Looking North

Figure D-4 View of Dulles Meteorological Station Looking Northeast

Figure D-5 View of Dulles Meteorological Station Looking East

Figure D-6 View of Dulles Meteorological Station Looking Southeast

Figure D-7 View of Dulles Meteorological Station Looking South

Figure D-8 View of Dulles Meteorological Station Looking Southwest

Figure D-9 View of Dulles Meteorological Station Looking West

Figure D-10 View of Dulles Meteorological Station Looking Northwest

Appendix E

30-years of Monthly Precipitation Data from the Southeast Regional Climate Center (SERCC)

WASHINGTON WB CHANTILLY, VIRGINIA

Monthly Total Precipitation (inches)

(448903)

File last updated on Dec 22,
*** Note *** Provisional Data *** After Year/Month 200908
a = 1 day missing, b = 2 days missing, c = 3 days, ..etc..,
z = 26 or more days missing, A = Accumulations present
Long-term means based on columns; thus, the monthly row may not
sum (or average) to the long-term annual value.
MAXIMUM ALLOWABLE NUMBER OF MISSING DAYS : 5
Individual Months not used for annual or monthly statistics if more than 5 days are missing.
Individual Years not used for annual statistics if any month in that year has more than 5 days missing.

YEAR (S)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
1962	0.00 z	0.00 z	0.00 z	0.00 z	0.00 z	0.00 z	0.00 z	0.00 z	0.00 z	0.00 z	0.00 z	0.00 z	0.00
1963	0.00 p	0.00 n	4.34	1.17	1.52	8.59	1.25	4.70	3.30	0.00	7.83	2.26	34.96
1964	5.56	4.50	2.82	3.68	0.80	1.36	3.09	2.49	3.72	1.96	1.80	4.19	35.97
1965	3.24	2.58	4.27	2.53	1.77	1.75	3.94	3.75	2.28	1.87	0.46	0.42	28.86
1966	4.22	3.90	1.24	4.38	3.84	0.94	2.17	1.79	9.39	3.01	1.50	3.67	40.05
1967	1.12	2.18	4.74	0.93	4.37	1.68	3.38	9.28	0.62	2.79	2.61	5.69	39.39
1968	2.31	0.68	3.36	1.29	5.90	5.20	4.08	4.90	2.10	2.77	3.57	2.32	38.48
1969	2.07	1.69	2.04	1.34	0.99	5.55	4.90	5.07	4.89	0.85	2.11	6.74	38.24
1970	1.32	2.76	2.98	4.19	2.86	2.48	6.00	2.65	1.03	2.79	6.00	3.88	38.94
1971	2.27	4.68	2.27	2.56	8.47	2.81	2.15	4.45	3.63	9.19	3.13	1.00	46.61
1972	2.28	5.44	2.37	4.40	4.76	18.19	1.53	2.09	1.40	3.44	7.09	6.06	59.05
1973	2.25	2.84	2.66	7.35	3.97	1.91	4.99	3.18	3.14	2.67	0.81	5.72	41.49
1974	3.07	1.14	3.09	2.14	3.78	5.41	2.69	4.84	4.02	0.71	1.97	5.26	38.12
1975	2.76	1.97	4.38	2.58	2.99	7.08	6.25	5.38	11.26	2.34	1.64	4.01	52.64
1976	2.81	1.42	4.15	1.31	4.18	2.88	2.33	3.13	3.75	7.88	0.57	1.78	36.19
1977	1.10	0.49	3.59	2.58	2.33	3.09	3.25	4.18	1.74	4.19	4.51	4.87	35.92
1978	6.55	0.25	2.85	1.62	5.05	4.36	4.52	4.29	0.78	0.79	3.02	3.58	37.66
1979	6.61	5.75	3.50	2.05	4.89	4.64	2.18	6.05	7.58	8.65	2.65	0.88	55.43
1980	2.95	1.00	4.82	3.64	3.86	1.89	4.41	1.67	2.70	2.77	3.42	0.68	33.81
1981	0.40	4.10	0.99	3.05	4.36	3.86	4.05	3.55	2.07	3.00	0.24	2.46	32.13
1982	2.10 a	4.09	3.47	2.82	3.57	5.49	2.11	3.36	4.22	2.21	2.87	2.25	38.56
1983	1.40	3.74	4.21	7.24	3.63	4.01	0.94	1.34	2.95	6.00	5.06	5.66	46.18
1984	1.42	4.13	5.81	5.01	4.23	2.19	2.46	10.71	1.49	1.73	3.64	1.25	44.07
1985	2.32	3.73	1.70	0.33	4.82	1.14	2.34	3.35	2.96	4.06	5.27	0.92	32.94
1986	1.58	3.16	1.12	3.01	1.19	1.40	1.86	5.72	1.04	1.30	4.17	4.83	30.38
1987	4.53	2.47	1.46	4.61	2.33	3.38	3.04	0.96	8.11	2.51	5.02	2.35	40.77
1988	2.47	2.06	2.31	2.35	10.26	0.52	7.12	3.92	1.80	1.60	4.48	0.92	39.81
1989	2.65	2.50	4.01	2.70	7.71	5.75	5.99	0.76	3.14	4.73	2.68	1.72	44.34
1990	3.14	1.65	2.78	5.06	4.37	1.77	5.42	5.56	1.49	6.53	2.56	5.00	45.33
1991	2.67	0.81	5.16	1.80	1.51	6.58	2.64	0.99	3.25	1.37	2.70	4.54	34.02
1992	2.13	2.26	3.23	3.15	3.82	2.88	7.23	1.33	5.55	2.81	5.24	4.73	44.36
1993	2.72	2.74	7.65	5.62	2.85	1.77	2.06	4.68	4.66	2.15	6.28	3.78	46.96
1994	4.12	3.61	6.71	1.71	3.19	5.82	5.75	4.62	3.40	1.05	1.86	2.42	44.26

1995	4.18	1.80	1.39	2.14	5.13	3.25	4.24	2.02	2.74	6.51	4.75	2.05	40.20
1996	5.61	2.62	3.52	3.69	7.07	4.88	5.89	4.16	7.72	3.97	3.75	5.21	58.09
1997	2.16	2.16	4.78	2.18	2.87	2.36	1.38	5.32	3.16	2.75	5.48	1.92	36.52
1998	5.43	5.83	5.60	2.92	4.52	5.87	1.31	0.44	1.25	1.50	1.21	1.53	37.41
1999	5.39	2.62	3.44	2.68	2.22	3.00	2.56	5.43	9.32	2.55	1.72	2.67	43.60
2000	2.50	1.92	3.35	4.36	2.57	4.02	4.28	5.90 b	4.20	0.06	1.57	2.06	36.79
2001	2.54	1.68	4.14	2.15	3.88 c	4.83	4.24	4.52	3.39	1.42	0.81	1.56	35.16
2002	1.22	0.46	3.48	3.45	4.73	3.61	2.64	2.91	2.84	5.04	4.13	3.61	38.12
2003	2.69	6.27	3.69 a	2.71	8.71	8.33	6.06	5.55	7.26	4.63	5.20	4.57	65.67
2004	1.41	1.93	2.05	5.04	3.06	3.73	3.72	3.79	5.80	1.04	4.11	3.01	38.69
2005	3.14	1.41	3.93	4.34	4.86	1.92	7.85	2.32	0.15	9.22	2.49	2.92	44.55
2006	2.39	2.38	0.07	4.86	1.80	11.79	2.45	1.24	7.12	4.82	5.31	1.74	45.97
2007	2.11	2.54	2.93	3.38	0.34	2.92	1.75	1.67	1.40	3.52	1.49	2.97	27.02
2008	1.26	2.67	2.47	6.22	9.38	4.21	2.18	2.48	7.18	1.31	2.01	2.61	43.98
2009	2.64	0.35	2.41	4.12	10.26	6.69	2.18	2.75	1.83	5.71	3.71	2.48 u	42.65

Period of Record Statistics

MEAN	2.84	2.63	3.35	3.24	4.16	4.21	3.59	3.73	3.80	3.27	3.29	3.14	41.17
S.D.	1.47	1.50	1.49	1.58	2.39	3.08	1.79	2.07	2.61	2.33	1.83	1.67	7.83
SKEW	1.00	0.59	0.44	0.64	0.97	2.34	0.62	0.96	1.01	1.05	0.38	0.30	1.03
MAX	6.61	6.27	7.65	7.35	10.26	18.19	7.85	10.71	11.26	9.22	7.83	6.74	65.67
MIN	0.40	0.25	0.07	0.33	0.34	0.52	0.94	0.44	0.15	0.00	0.24	0.42	27.02
NO YRS	46	46	47	47	47	47	47	47	47	47	47	46	45