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In-stack Plume Opacity from Electrostatic Precipitator/Scrubber System at Harrington Unit 1

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EPA REVIEW NOTICE

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In-stack Plume Opacity from Electrostatic Precipitator/Scrubber System at Harrington Unit 1

by

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ABSTRACT

Results of theoretical modeling of particulate emission and in-stack plume opacity for the electrostatic precipitator (ESP)/scrubber system at Southwestern Public Service Company's Harrington Unit 1 are presented. The theoretical results of an emission rate of 17.8 ng/J and opacity of 35% are in good agreement with data from compliance testing of the unit. The calculations indicate that 20% opacity can be achieved (1) by increasing specific collector area (SCA) of the ESP by 25% and leaving the scrubber pressure drop alone, (2) by increasing scrubber pressure drop by a factor of 4 and leaving the ESP alone, (3) by replacing the existing marble bed scrubber with a venturi scrubber, increasing the pressure drop by 20%, and leaving the ESP alone, or (4) by doubling the SCA of the ESP and removing the scrubber. Calculations showing the impact of high in-stack opacity on the downwind appearance of plume are also included.

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NOMENCLATURE

d_g	-	Geometric mass mean particle diameter, μm
f	-	Empirical factor in scrubber model
H	-	Effective height of emission, m
I	-	Intensity of light transmitted through aerosol
I_o	-	Intensity of light source
K	-	Light scattering parameter, $cm^3\ m^{-3}\ m^{-1}$
L	-	Optical path length, m
m	-	Particle refractive index
O_D	-	Downwind plume opacity
O_s	-	In-stack plume opacity
Q	-	Gas flow rate, m^3/s
u	-	Wind speed, m/s
W	-	Mass concentration of particulate, g/m^3
ξ_y	-	Plume transmittance dispersion parameter, m^{-1}
ρ_p	-	Particle density, g/cm^3
σ_g	-	Geometric standard deviation
σ_z	-	Verticle plume dispersion coefficient

ACKNOWLEDGEMENTS

The assistance of Dr. Phil Lawless with the ESP modeling is gratefully acknowledged. The cooperation of Southwestern Public Service Company and the willingness of SWPS to provide data for this study are greatly appreciated.

CONCLUSIONS

The results reported in this report show that the opacity measured at Southwestern Public Service Company's Harrington Unit 1 is what one should expect from an electrostatic precipitator (ESP)/marble bed scrubber system. The results are consistent with the calculations of Sparks et al.[1] who showed that the particle size distribution created by ESP/venturi scrubber systems is likely to be optically active.

The steps that can be taken to achieve 20% opacity at Unit 1 are:

1. Increase ESP specific collector area (SCA) by 25% and leave scrubber pressure drop the same.
2. Increase scrubber pressure drop by a factor of 4 and leave the ESP alone.
3. Double the ESP SCA and remove the scrubber.
4. Replace the marble bed scrubber with a venturi scrubber, increase pressure drop by 20%, and leave the ESP alone.

None of these steps appear economically attractive. Future installations that use ESP/scrubber systems should select venturi scrubbers to minimize the energy consumption necessary to meet opacity standards. A plant with particulate emissions that meet the mass standard but exceed the opacity standard will emit more fine particulate matter and have a greater impact on visibility downwind from the plant than will a plant with particulate emissions that meet both standards.

RECOMMENDATIONS

More research on the plume opacity from ESP/scrubber systems is needed. Although the results at Harrington Unit 1 are consistent with model predictions, the possible effects of particle creation or growth due to combined effects of SO_2, SO_3, and moisture cannot be ignored. These effects will likely be important and, in fact, may be dominant in situations where high sulfur coal is burned.

Research on prediction of plume opacity from particulate control devices should be encouraged.

INTRODUCTION

Particulate air pollution control regulations generally limit both the mass of particulate that can be emitted and the opacity of the plume. It is generally assumed that the two regulations are compatible; i.e., if a plant meets the mass emission standard it will also meet the plume opacity standard.

Recent theoretical results and laboratory scale experiments with a particulate control system which consisted of an electrostatic precipitator (ESP) followed by a scrubber indicate that the mass emissions required to meet a given opacity limit may be very much lower than the mass emission standard.[1] Recent compliance tests of the ESP/scrubber system at Southwestern Public Service Company's (SWPS) Harrington Unit 1 showed a mass emission of about 19.4 ng/J (0.045 $lb/10^6$ Btu) and an opacity of over 30%: this is in line with results of Sparks et al.[1] The mass emission is well under the current New Source Performance Standard (NSPS) of 43 ng/J (0.1 $lb/10^6$ Btu) but the opacity exceeds the standard of 20%.

SWPS has requested an adjustment of the opacity standard as it applied to Unit 1. EPA's Division of Stationary Source Enforcement (DSSE) has requested assistance from the Particulate Technology Branch of EPA's Industrial Environmental Research Laboratory, Research Triangle Park (IERL-RTP) to determine the reasonableness of the SWPS request. This report is the result of that request.

A theoretical study of the particulate control system at Harrington Unit 1 was undertaken to:

1. Estimate the opacity of emissions from the existing system.
2. Estimate the scrubber pressure drop required to meet the 20% opacity standard with the existing ESP specific collector area.

3. Estimate the ESP specific collector area required to meet the 20% opacity standard with the existing scrubber pressure drop.
4. Estimate the ESP specific collector area required to meet the 43 ng/J mass standard and 20% opacity standard if the scrubber were eliminated.

Additional calculations not specifically related to SWPS were performed to:

1. Estimate the impact on downwind plume opacity if the in-stack opacity standard is not met.
2. Estimate the scrubber pressure drop required to meet the 20% opacity standard if a venturi scrubber were used instead of a marble bed scrubber.

Data necessary to carry out the theoretical calculations were provided by Southwestern Public Service Company.

POSSIBLE REASONS FOR EXCESSIVE OPACITY

Several possible explanations of the high opacity at Harrington 1 have been suggested. The most plausible are:

1. Creation of submicron particles due to inefficient entrainment separation.
2. Creation of submicron particles due to reactions of SO_2 or SO_3 with water in the plume.
3. Creation of submicron particles due to water condensation.

Although the above three factors may influence the opacity at Unit 1, it seemed likely that the opacity/mass concentration relationship at Harrington Unit 1 was similar to that reported by Sparks et al.[1] in their theoretical analysis of particle collection by ESP/scrubber systems.

Therefore, extensive modeling of the ESP/scrubber system was undertaken to predict the plume opacity of the current system and to estimate what changes in the system would be necessary to achieve an opacity of less than 20%.

DESCRIPTION OF THE SYSTEM

The steam generator for Harrington Unit 1 is a Combustion Engineering, Inc. boiler, tangentially fired, capable of producing 1,219,265 kg of steam/hour at 170 atm and 540°C while firing approximately 180,000 kg/hour of pulverized coal. The primary fuel for this unit is a low-sulfur coal transported to Amarillo by rail from Gillette, Wyoming. A proximate/ultimate analysis is given in Table 1.

The ESP/scrubber system at Unit 1 consists of a conventional ESP followed by a marble bed scrubber. The design data for the system are shown in Table 2. The full load compliance tests, Table 3, indicate that the system is performing somewhat better than designed.

PARTICLE SIZE DATA

SWPS provided particle size distribution data for the ESP inlet and ESP outlet, shown in Table 4. These data were used to estimate the empirical factors in the ESP and scrubber models.

MODELS

ESP MODEL

The ESP computer model described by McDonald[2] was used to model the ESP. Input data for the model were provided by SWPS and are shown in Table 5. The performance data provided by SWPS were used to estimate sneakage, nonrapping reentrainment, and gas flow distribution factors in the model. The agreement between the model predictions and the data is good as shown in Figure 1. The empirical factors used in further modeling

Table 1. ANALYSIS OF COAL BURNED AT HARRINGTON #1[a]

Proximate Analysis - As Received

	Typical,%	Range,%
Moisture	28.26	22.59 - 34.52
Ash	4.74	3.69 - 8.79
Volatile	32.00	27.39 - 38.04
Fixed Carbon	35.00	30.96 - 40.02
	100.00	
Cal/g	4680	4314 - 5113
Sulfur, %	0.33	0.09 - 0.59
SO_2, ng/J	332	86 - 590

Ultimate Analysis - As Received

	Typical,%	Range,%
Moisture	28.39	23.40 - 34.52
Carbon	50.03	45.26 - 53.70
Hydrogen	3.54	2.84 - 4.13
Nitrogen	0.69	0.41 - 1.02
Chlorine	0.01	0.00 - 0.16
Sulfur	0.33	0.09 - 0.59
Ash	4.73	3.69 - 6.64
Oxygen	12.28	10.25 - 15.00
	100.00	
Equilibrium Moisture	24.76	19.23 - 27.33
Cal/g at Equilibrium Moisture	4910	4765 - 5427
Hardgrove Grindability Index	53.27	37.00 - 67.80

[a]Data provided by Southwestern Public Service Company.

Table 2. DESIGN SPECIFICATIONS FOR PARTICULATE CONTROL AT HARRINGTON #1

Gas Flow Rate	2.571×10^6 Am^3/h @/56°C
Electrostatic Precipitator Collector Area	4.067×10^4 m^2
Electrostatic Precipitator Design Efficiency	95%
Marble Bed Scrubber Pressure Drop (scrubber only)	17.8 cm H_2O
Marble Bed Scrubber Design Efficiency	50%
Total System Design Efficiency	97.5%
Liquid-to-Gas Flow Rate Ratio	4×10^{-3} m^3/m^3
Gas Velocity Through Marble Bed	1.98 m/s
Reheat Entrance Temperature	52°C
Reheat Exit Temperature	72°C
Stack Diameter	8.23 m

Table 3. PERFORMANCE OF PARTICULATE CONTROL SYSTEM AT HARRINGTON #1

Flyash Concentration, ESP Inlet	4.03 g/dNm^3 [a]
Flyash Concentration, ESP Outlet	0.18 g/dNm^3
ESP Efficiency	95.5%
Flyash Concentration, Scrubber Inlet	0.18 g/dNm^3
Flyash Concentration, Scrubber Outlet	0.069 g/dNm^3
Scrubber Efficiency	62.5%
System Efficiency	98.3%
Particulate Emission Rate	19.4 ng/J

[a] dNm^3 means dry normal cubic meter

Table 4. PARTICLE SIZE DATA FOR HARRINGTON #1[a]

Load 350 MW[b]					
ESP Inlet Run #1			ESP Outlet[c]		
Stage	d_{50}, μm	Cumulative fraction less than	Stage	d_{50}, μm	Cumulative fraction less than
1	27.5	0.796	1	24	0.777
2	12	0.388	2	9.5	0.744
3	5.25	0.215	3	4.5	0.576
4	2.1	0.109	4	1.8	0.296
5	1.25	0.0709	5	0.97	0.0916
6	0.59	0.0651	6	0.48	0.0191
7	0.31	0.0616	7	0.25	0.00880
ESP Inlet Run #2					
1	19	0.453			
2	8.5	0.334			
3	3.9	0.223			
4	1.6	0.105			
5	0.85	0.0481			
6	0.45	0.0275			
7	0.22	0.0206			

[a]All data furnished by Southwestern Public Service Company

[b]All data for 350 MW

[c]Only one run at ESP outlet

Table 5. INPUT DATA FOR ESP MODELING OF HARRINGTON #1

Inlet Particle Size Distribution--as given in Table 3

Number of Electrical Sections--4

Plate Collector Area Per Section--1.018×10^4 m^2

Section 1:

Applied Voltage--2.345×10^4 volts; average current density--13.3 na/cm^2

Section 2:

Applied Voltage--2.446×10^4 volts; average current density--13.8 na/cm^2

Section 3:

Applied Voltage--3.080×10^4 volts; average current density--13.3 na/cm^2

Section 4:

Applied Voltage--2.814×10^4 volts; average current density--13.2 na/cm^2

Ion Mobility--$2.826 \times 10^{-4} m^2/V\text{-}s$

Wire Radius--1.284×10^{-3}m

Wire-to-Wire Spacing--0.228 m

Plate-to-Plate Spacing--0.228 m

Sneakage and Nonrapping Reentrainment Factor--0.1

Standard Deviation of Gas Velocity--0.50

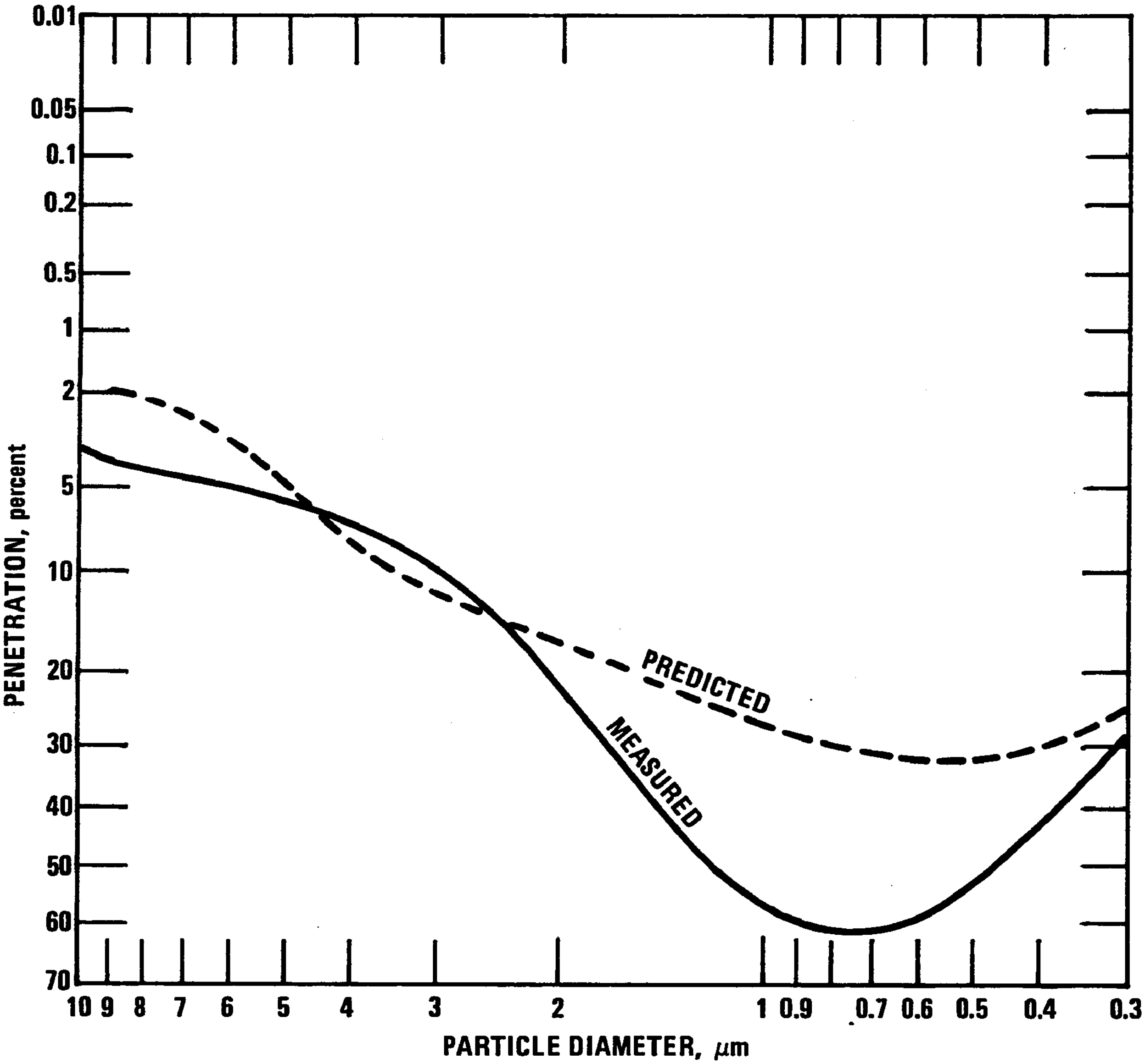

Figure 1. Comparision of measured and predicted ESP performance

are also given in Table 5.

SCRUBBER MODEL

Scrubber performance was modeled by modifying a venturi scrubber model[3,4] so that it fit the full load penetration data provided by SWPS. A value of 0.2 for the empirical factor f gave the required agreement.

The particle size distribution predicted by the scrubber model was compared with data supplied by SWPS for 300 MW operation. A log-normal fit was calculated for both the measured and predicted size distributions. The results were:

d_g measured = 0.796 μm	d_g predicted = 0.906 μm
σ_g measured = 4.5	σ_g predicted = 3.05

With all the uncertainties in both the data and the calculations, the agreement between the measured and predicted size distribution is good. The predicted values of d_g and σ_g fall within the 90% confidence interval for the log-normal fit for the measured data.

All scrubber calculations were performed using a Texas Instruments TI-59 calculator.

OPACITY MODEL

The opacity of the plume was estimated using a technique developed by Ensor.[5] Ensor has shown that

$$I/I_o = \exp\left[- \frac{WL}{K\rho_p} \right] \qquad (1)$$

where I/I_o = transmittance through the plume (1 - opacity)
W = mass concentration of particles, g/m^3
L = optical path length, m
ρ_p = particle density, g/cm^3

K = parameter describing effects of particle size distribution, wavelength of light, and refractive index of particles, $cm^3\ m^{-3} m^{-1}$

The parameter K was calculated on a TI-59 using estimation procedures reported by Deirmendjian.[6] K calculated by this technique is in good agreement with the results calculated by Ensor using complete solutions.

MODELING TECHNIQUE

The particle size distribution exiting the ESP was used as the input particle size distribution for the scrubber model.

The predicted scrubber outlet size distribution was used to calculate parameter K which was then used to calculate the plume opacity from Equation 1. The refractive index and density of the particles were adjusted until agreement between model and measured data was obtained. The density selected was 2.4 g/cm^3 (which is in good agreement with fly-ash densities reported by others). The refractive index, m, selected was 1.38 - 0.02i. Changes in refractive index did not greatly change the calculated results. The model predictions for the existing system are shown in Table 6.

As can be seen from Table 6, the plume opacity at Unit 1 is very close to the measured value. Thus, it is fair to say, that the plume opacity at Unit 1 is the opacity that would be expected from the particulate control system.

The reason for the opacity at Harrington Unit 1 is the same as that discussed by Sparks et al.[1] Namely, the particle size distribution created by an ESP scrubber system designed to give a given mass emission is much more optically active than the particle size distribution from an ESP alone.

Table 6. COMPARISON OF PREDICTED AND MEASURED EMISSIONS AND OPACITY FOR HARRINGTON #1

	Measured	Predicted[a]
Emission	19.4 ng/J	17.8 ng/J
Opacity	37%	35%
Scrubber Pressure Drop	18 cm H_2O	18 cm H_2O
Scrubber Efficiency	0.62	0.65

[a]Predictions based on $f = 0.2$, $\rho_p = 2.4$ g/cm^3, and $m = 1.38 - 0.02i$

STEPS NECESSARY TO ACHIEVE 20% OPACITY

The situation at Unit 1 was examined to determine what steps could be taken to comply with the 20% opacity limit. Three cases were examined.

1. Leaving the scrubber alone and modifying the ESP.
2. Removing the scrubber and modifying the ESP.
3. Leaving the ESP alone and increasing the pressure drop across the scrubber.

The results of the calculations are:

Case 1 - The model predictions indicate that a 25% increase in specific collector area would be required to meet the 20% opacity limit.

Case 2 - The ESP model predicts that the SCA of the existing ESP would have to be doubled to comply with 40 ng/J and 20% opacity.

Case 3 - The results of Case 3 studies are shown in Table 7 and Figure 2. Note that the pressure drop across the scrubber would have to be increased by more than a factor of 4 to meet 20% opacity.

OPACITY IF A VENTURI SCRUBBER WERE USED

Harmon and Sparks[7] have reported that venturi scrubbers are the most energy efficient unaugmented type of scrubber. Thus it is of interest, at least for new installations, to determine the pressure drop necessary to give 20% opacity with a venturi scrubber instead of a marble bed scrubber.

The venturi scrubber model with f = 0.5 accurately predicts the performance of venturi scrubbers as is shown in Figure 3 taken from Reference 7. The predicted particulate emissions rates and plume opacities for a system identical to that at Harrington #1 (except that the marble bed scrubber is replaced by a venturi scrubber) are shown in Table 8.

Table 7. CALCULATED EMISSIONS AND OPACITY AT VARIOUS SCRUBBER PRESSURE DROPS FOR EXISTING MARBLE BED SCRUBBER[a]

Scrubber Pressure Drop, cm H_2O	Penetration	Efficiency	Emission ng/J	Opacity %
19	0.350	0.650	17.8	35
32	0.278	0.722	14.2	30
48	0.226	0.774	11.5	25
64	0.192	0.808	9.8	20
167	0.101	0.899	5.1	12

[a]All calculations based on f = 0.2, ρ_p = 2.4 g/cm^3, and m = 1.38 - 0.02i

Table 8. CALCULATED EMISSIONS AND OPACITY FOR ESP WITH VENTURI SCRUBBER[a]

Pressure Drop cm H_2O	Scrubber Penetration	Scrubber Efficiency	Emission ng/J	Opacity %
19	0.0734	0.927	3.7	13
36	0.0355	0.965	1.8	7

[a]All calculations based on f = 0.5, ρ_p = 2.4 g/cm^3, and m = 1.38 - 0.02i

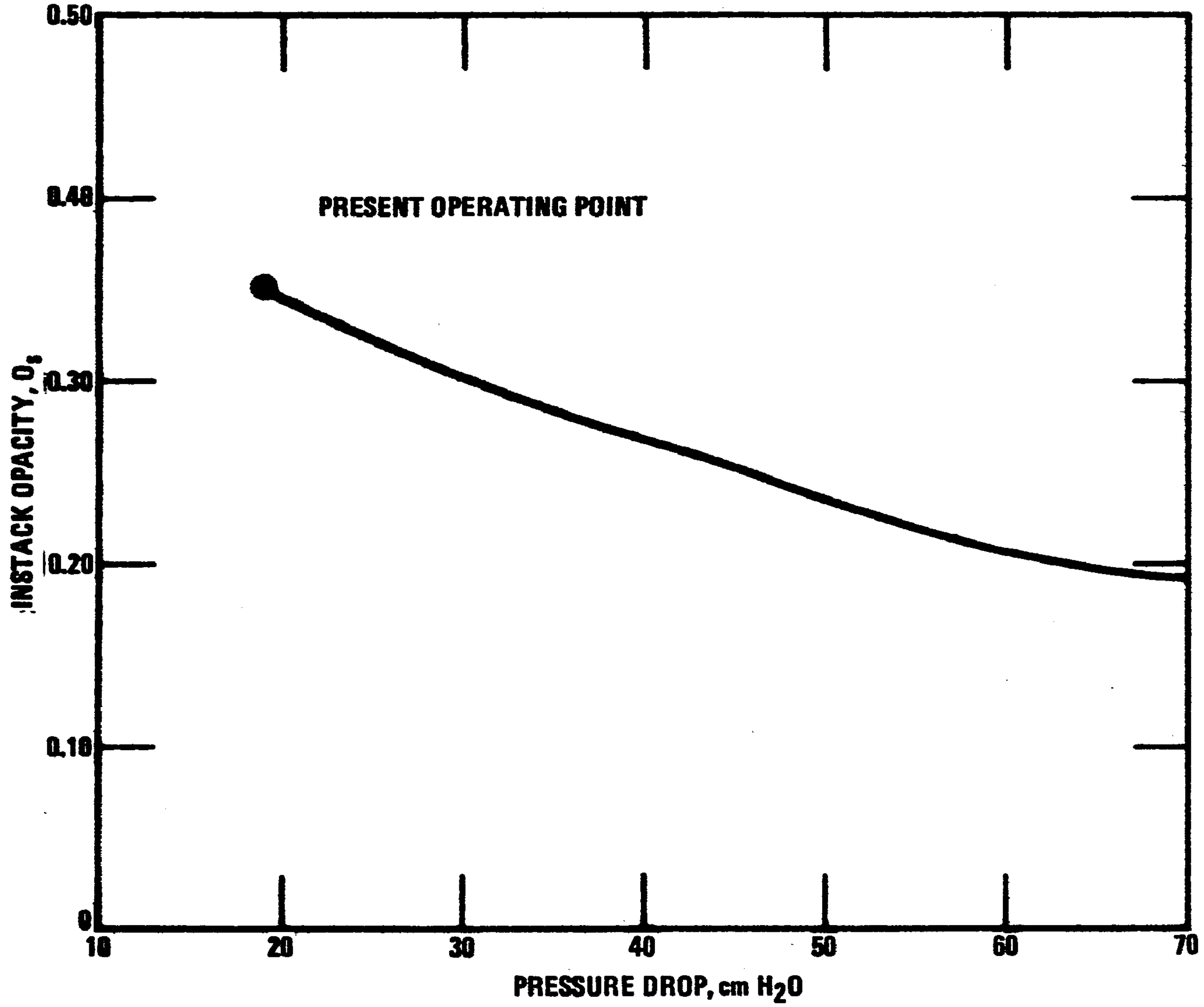

Figure 2. Predicted plume opacity versus marble bed scrubber pressure drop for Harrington number 1.

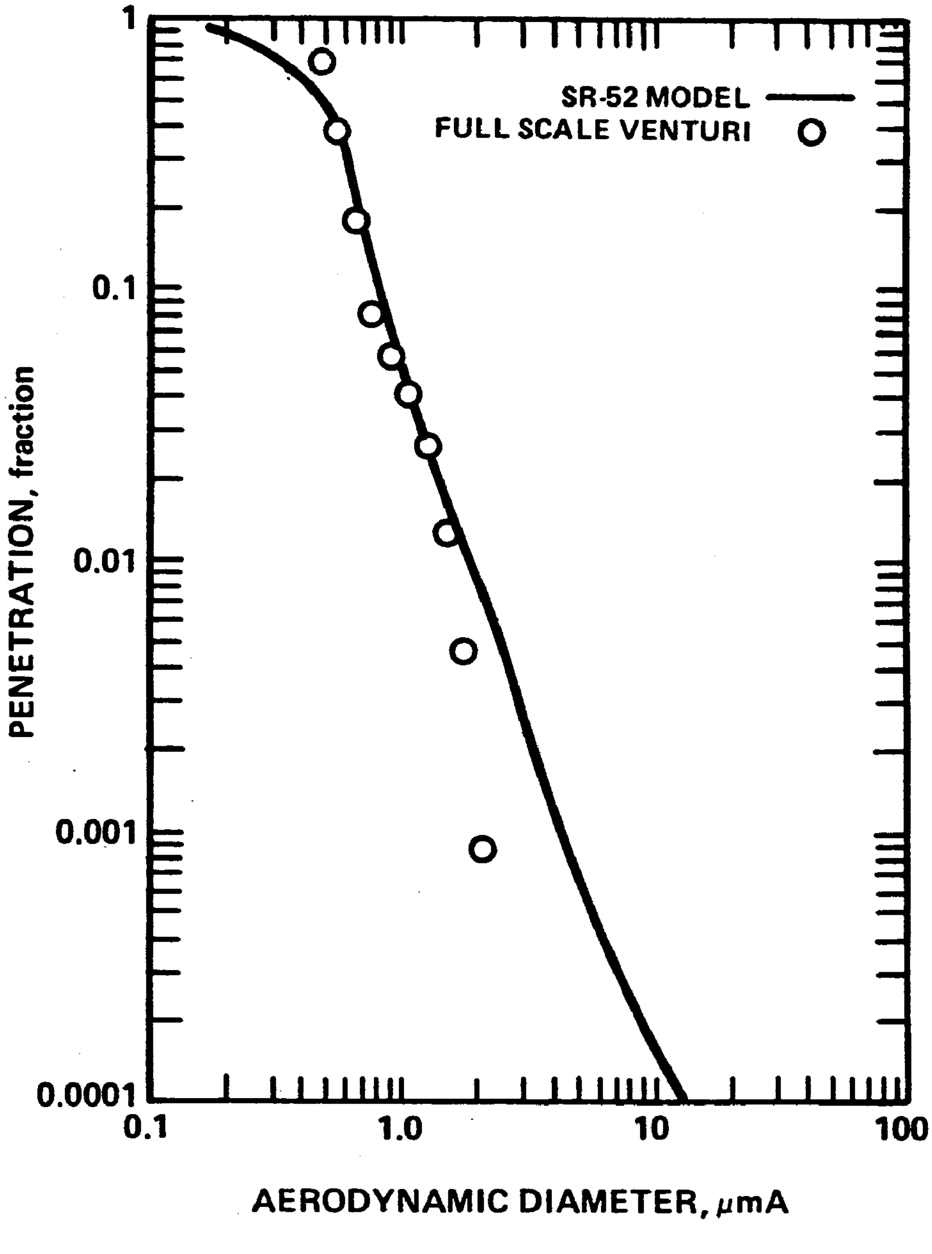

Figure 3. Comparison of graded penetration curve predicted by venturi model program with field data for a variable throat venturi scrubber operating at a venturi pressure drop of 48 cm w.c. collecting fly ash.

These calculations indicate that, even if opacity standards must be met, an ESP/venturi scrubber system should be considered.

ACCURACY OF THE CALCULATIONS

The accuracy of the predicted plume opacity depends on two factors--the accuracy of the mathematical models and the accuracy of the data used in the models. These are two separate problems. Each is discussed below.

The data used both to "calibrate" the models and as input to the models were provided by SWPS. There is no absolute way to assess the accuracy of these data. The data do seem reasonable. The inlet particle size distribution is within the range one would expect for coal fired boilers. The ESP outlet particle size distribution (the scrubber inlet particle size distribution) is also reasonable.

The scrubber model used in the calculations may be a source of error. Calvert's venturi scrubber model with a value of f = 0.2 was used. Although the venturi scrubber model with f = 0.2 predicted the overall penetration for full load of the existing system operated at a pressure drop of 18 cm H_2O, there are no data to show that the venturi model with f = 0.2 would predict the performance of the marble bed scrubber at higher pressure drops. However, it is unlikely that the marble bed scrubber would be more efficient at higher pressure drops than predicted by the model.

Probably the major source of uncertainty in the calculated results lies in the opacity predictions. The opacity predictions are based on a log-normal fit to the outlet particle size distributions. Unfortunately, the outlet particle size distributions were never log-normal. A rough estimate of the uncertainty in the opacity predictions caused by the assumption of log-normal size distribution can be obtained by calculating opacity for log-normal size distributions with d_g and σ_g values at the 90% confidence level of the fitted log-normal size distribution.

The range of estimated opacity shown in Table 9 is not a true statistical 90% confidence limit for the predicted opacity. Rather it is an indication of the overall uncertainty in the predicted opacity. Methods of predicting opacity are under development which do not require the log-normal assumption.

POSSIBLE ENVIRONMENTAL IMPACT OF FAILURE TO MEET THE OPACITY STANDARD

For a given mass emission, stack diameter, and particle refractive index, the plume opacity from a source is a function of the particle size distribution: the higher the opacity, the finer the particle size distribution. Thus, a plant meeting the New Source Performance Standard for mass but exceeding the NSPS for opacity will emit more fine particulate matter than will a plant meeting both standards.

The opacity of the plume at the stack also affects the downwind appearance of the plume (in the absence of secondary particulate formation). Ensor et al.[8] have shown that the downwind opacity of a plume is given by

$$O_D = 1 - \exp\left[- \frac{\xi_y WQ}{\rho_p K u} \right] \qquad (2)$$

where O_D is downwind opacity as observed by an observer looking across the plume

Q is the gas flow rate, m^3/s

ξ_y is a parameter based on plume dispersion, m^{-1}

$$= \frac{1}{\sqrt{2\pi}\sigma_z} \left[1 + \exp\left(-2 H^2/\sigma_z^2\right)\right]$$

u is the wind speed, m/s

W is the mass concentration of particulate, g/m^3

K is the light scattering parameter, $cm^3\ m^{-3} m^{-1}$

H is the height of the emission, m

σ_z is the vertical plume dispersion coefficient

Table 9. ESTIMATED RANGE OF OPACITIES FOR EXISTING ESP AND VARIOUS MARBLE BED SCRUBBER PRESSURE DROPS

Scrubber ΔP, cm H_2O	Predicted Opacity, %	Range of Opacity for 90% Confidence Limits on Log-Normal Parameters, %
19	35	30 - 43
32	30	26 - 43
64	21	18 - 26

Equation (1), which relates K to in-stack opacity, O_s, can be substituted into equation (2) to give

$$O_D = 1 - \exp\left[\frac{\varepsilon_y Q \ln(1-O_s)}{uL}\right]$$

Calculations, using equation (3) for a 300 MW power plant with a particulate emission rate of 17 ng/J and an in-stack opacity of 40% and emissions of 34 ng/J and an in-stack opacity of 20%, are shown in Figure 4.

The plume for the Case $O_s = 0.2$ will probably not be visible when the downwind distance exceeds say 0.5 km. However, the plume for the Case $O_s = 0.4$ will probably be visible until the downwind distance exceeds 2-3 km.

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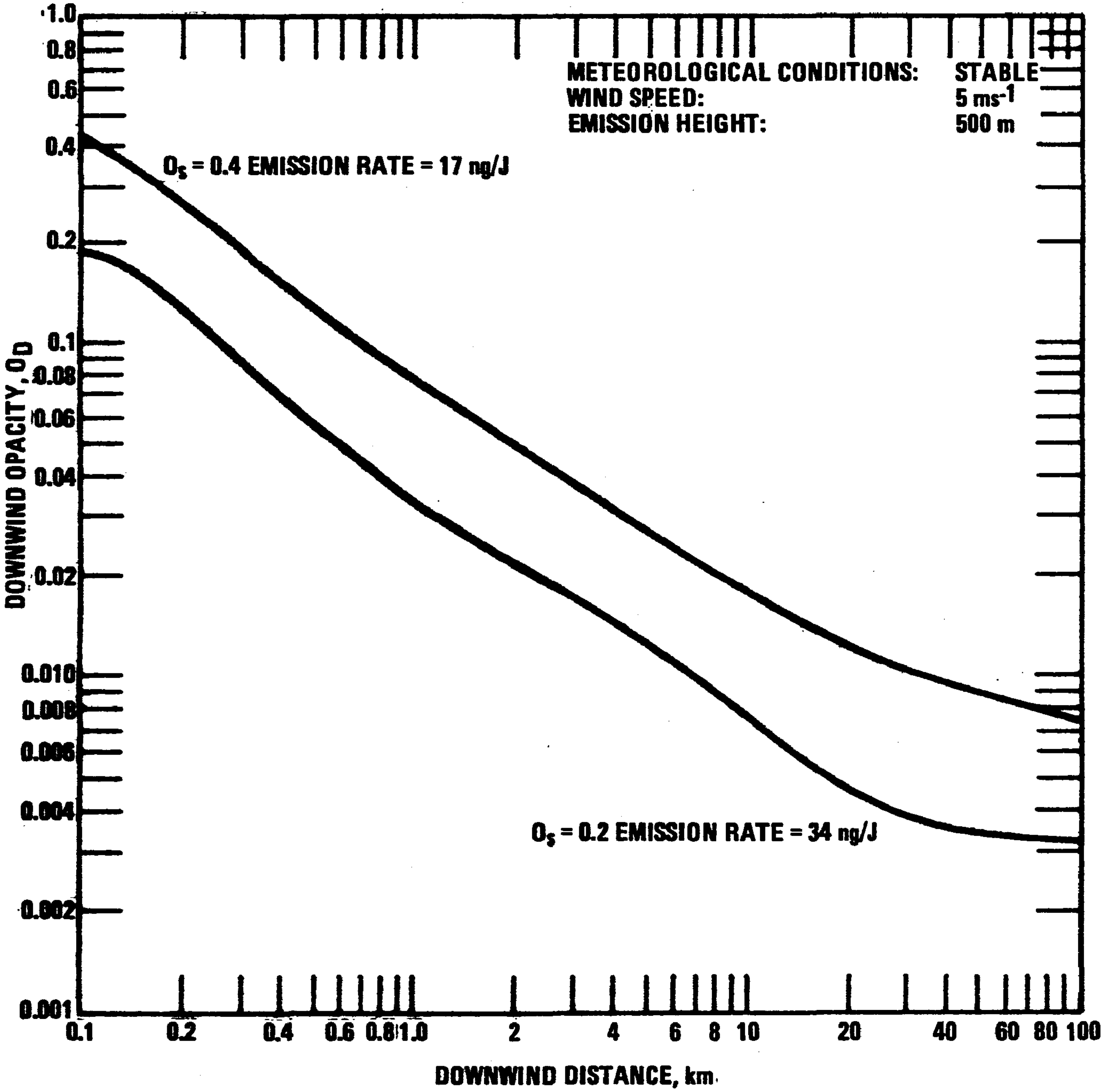

Figure 4. Predicted downwind opacity for 300 MW plant with indicated emission rates and in-stack opacities.

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16. ABSTRACT The report gives results of theoretical modeling of particulate emission and in-stack plume opacity for the electrostatic precipitator (ESP)/scrubber system at Southwestern Public Service Company's Harrington Unit 1. The theoretical results of an emission rate of 17.8 ng/J and opacity of 35% are in good agreement with data from compliance testing of the unit. The calculations indicate that 20% opacity can be achieved (1) by increasing specific collector area (SCA) of the ESP by 25% and leaving the scrubber pressure drop alone, (2) by increasing scrubber pressure drop by a factor of 4 and leaving the ESP alone, (3) by replacing the existing marble bed scrubber with a venturi scrubber, increasing the pressure drop by 20%, and leaving the ESP alone, or (4) by doubling the SCA of the ESP and removing the scrubber. Calculations showing the impact of high in-stack opacity on the downwind appearance of the plume are also included.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Gas Scrubbing	Pollution Control	13B	13H
Flue Gases	Dust	Stationary Sources	21B	11G
Opacity	Mathematical	Particulate	14B	
Plumes	Modeling			12A
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