AN EVALUATION AND COMPARISON OF THE EPRI ESPMGEMS ELECTROSTATIC PRECIPITATOR PERFORMANCE MODEL WITH FIELD DATA AND OTHER MODELS

Richard D. McRanie
Lesley S. Biller

Systems Applications International
P.O. Box 14348
Research Triangle Park, NC 27709
(919) 460-2500

Abstract

The Electrostatic Precipitator Performance Model (ESPMGEMS) was developed by Dr. Phil A. Lawless of Research Triangle Institute (RTI) under the sponsorship of The Electric Power Research Institute (EPRI). ESPMGEMS is a collection of several ESP related models based on over twenty years of research sponsored by EPRI and the U.S. Environmental Protection Agency (EPA). The Beta version of ESPMGEMS is currently being evaluated by several utilities. This paper presents a brief overview of ESPMGEMS and a comparison of actual performance data from three electrostatic precipitators (ESPs) with the results estimated by ESPMGEMS and two other ESP programs, a developmental version of ESPMGEMS and the Southern Research Institute (SORI) model.

Background

The first ESP models were developed from simple logarithmic correlations of performance with ESP size combined with fundamental theory by Deutsch. Subsequent work by Allander, Matts, Ohnfeld and White resulted in numerous correlations that tied together theory with actual field practice. More advanced models followed which applied highly detailed numerical models containing fundamental particle charging parameters, the most familiar being EPA/Southern Research Institute (EPA/SORI). In its original form the SORI model required a main frame computer to run. This was, of course, before the advent of the personal computer (PC). Later models adopted improved versions of EPA/SORI with additional features and flexibility, but the core calculations have remained fairly consistent.

With the wide availability of extremely powerful PCs, ESP models have been converted to run on the PC. ESPMGEMS is the latest version of the RTI ESP model and it is designed to run in the PC environment. ESPMGEMS not only performs the base ESP calculations but also incorporates several related computer models and correlations to produce a wide variety of ESP operational characteristic estimates.

It should be noted that any ESP model can produce misleading results in the hands of an inexperienced user. All models will produce inaccurate results if the user is not careful to ensure that the inputs reflect reality. An understanding of ESP operation and the model is essential to achieve accurate and useful results.

ESPMGEMS Overview

ESPMGEMS uses menu-driven software that operates on an IBM PC/AT or compatible. The computer must have a hard disk, a VGA monitor, 450,000 bytes of random access memory (RAM) available out of the typical 640,000 bytes of total RAM memory, and DOS Version 2.0 or higher. It is recommended that the hardware configuration include a fast 386 or 486 central processor with a fast hard disk and a math coprocessor.

ESPMGEMS can be used to check the operation of an ESP, evaluate the effectiveness of proposed corrections to its operation, and further used to evaluate the impact of changing operational parameters, such as switching fuels. The program consists of a core model and several subsidiary models and correlations. The core model of ESPMGEMS is a performance model which predicts the ESP collection performance from input parameters. If all input parameters are known, the model's predicted values should closely correspond to actual performance values. Unfortunately, some of the ESP data necessary to operate this performance model are difficult to obtain. ESPMGEMS provides auxiliary models and correlations to calculate or estimate input parameters if actual data are not available. However, the accuracy of the ESP performance predictions decrease when input parameters are estimated using the auxiliary models and correlations. Actual data should always be used whenever possible.

Auxiliary Models and Calculations

ESPMGEMS contains auxiliary models and correlations to calculate unavailable data in limited cases. These auxiliary models and correlations can be very useful, especially when evaluating fuel changes. Examples include calculations of coal combustion products, coal rank, ash electrical resistivity, particle size distributions, and voltage-current operating points.

"Combustion" performs coal-dependent gas calculations to establish flue gas parameters. The fuel heating value, burn rate, and composition are used to make this estimate. Predicted properties include volume, composition, and viscosity. "Coal Rank" calculates the coal rank and heating value from the supplied coal analyses. Selecting this option will change the program heating value, but will not change the combustion calculations, because "Combustion" also uses the calculated heating value.

"Resistivity" is based on the Bickelhaupt resistivity model which uses the ash chemistry to calculate resistivity for a cold-side (non-sodium-depleted) ESP resistivity curve over a temperature range of 200-800 °F. "Resistivity" uses the sulfur trioxide resistivity effects from the first Bickelhaupt model and the surface resistivity effects from the more advanced model. The resistivity value is set to that which is appropriate to the input ESP temperature. "Hot Resistivity" is based on a Bickelhaupt model that estimates resistivity for sodium depleted ash. These estimates are applicable after several weeks of operation of a hot-side ESP.

"Particle size" predicts particle size distributions and, where appropriate, mass loading. The size distributions can be viewed graphically as both cumulative and differential presentations. Extreme care should be taken in using particle size distributions. Any ESP model is very sensitive to the particle size distribution used by the model. Unfortunately, these measurements are difficult and expensive to make. Consequently, correlations are all that are frequently available. "EPRI V-I" estimates voltages, current densities, corona onset factors, and peak/average ratios from the ESP ash resistivity, the wave form, wire-plate spacing, and section order. The option is based on correlations derived from a number of measurements on cold side ESPs, similar to those derived by SORI.(1)

ESPM Performance Evaluation

To evaluate the accuracy of ESPMGEMS correlations and performance calculations, a series of comparisons were made between ESP performance results estimated by ESPMGEMS, SORI, and ESPMOLD, and with actual measured data. The specific results compared were the ESP efficiency or penetration, opacity, and emissions estimates. The estimations were generated using the different calculation modes, described below, for three different ESP data sets.

Calculation Models

The results were estimated using the four calculation modes incorporated in ESPMGEMS: Rapid, Detailed, Very Detailed, and Standard. These modes vary in the level of sophistication in their calculations. In addition, Standard is the only mode which matches the input current densities; whereas the other modes use calculated currents and current densities. The Rapid option is the most basic and quickest method. Rapid calculates performance using an analytical approximation for the electric field. The average voltage and the peak/average ratio are used instead of the actual electrical data. The Detailed calculation method is similar to Rapid, except that numerical methods are used to calculate the electric field and local current in the interelectrode space. This option requires more computer time than Rapid and produces more precise results. With the Very Detailed option, the calculation is performed for every half-wire interval. This is the most rigorous method and is four times slower than Detailed. The Standard mode is the default method of ESPMGEMS and is actually a combination of several calculation methods designed to match the current densities input in all sections. The particle size distribution, corona onset factor, gas velocities, and/or peak/average ratios may be adjusted as needed to match the current densities. ESPMOLD has Rapid, Detailed, and Very Detailed calculation modes similar to those of ESPMGEMS, and SORI has only Rapid and Very Detailed methods.

Both Rapid and Very Detailed calculations were performed for each data set using all three ESP programs. In addition, the data sets were run in the Detailed calculation mode for ESPMGEMS and ESPMOLD, and in the Standard mode for ESPMGEMS. It is assumed that users will generally run calculations in the Very Detailed mode, but the other modes were run for comparison.

Data Set Descriptions

Data from three different ESPs, which we call ESPs 1,2, and 3, were used as data sets in each of the three ESP programs. The three data sets are shown in Table 1. For every run of each data set, several variables were kept constant: the flue gas viscosity was 236 micropoise, the rapping mass median diameter was seven microns, the rapping standard deviation was 1.5, and the wave form was full wave (1:1). The calculations were performed for two different sets of non-ideal conditions; i.e. different sneakage and sigma values. Sneakage is the fraction of gas that bypasses the collection zone and sigma is the relative standard deviation of the gas velocity distribution. For the first non-ideal condition, the sneakage was 0.05 and sigma was 0.15. In the second run, the sneakage was 0.10 and the sigma was 0.25. These combinations of sneakage and sigma were selected because they cover the range of factors normally encountered in utility ESPs and should therefore bracket the actual ESP performance.

Table 1.
Comparison of the ESP Data Sets

	ESP 1	ESP 2	ESP 3
Number of Sections	5	4	4
Total SCA (ft^2/Kacfm)	235	174	162
ESP Width (ft)	120	207	161.3
ESP Length (ft)	30	24	24
ESP Height (ft)	30	30	30
Gas Volume (acfm)	1,103,600	2,280,000	3,555,556
Gas Velocity (ft/s)	5.1	6.1	6.1
Inlet Mass Loading (gr/acf)	0.8	1	0.7
Particle Density (g/cm^3)	2.5	2.5	2.3
Inlet Mass Median (Particle Diameter (microns))	18		15
Geometric Standard Deviation	5.7		6
Voltage by Section (kilovolts)			
Section 1	46.0	30.0	51.8
Section 2	46.0	32.4	44.3
Section 3	39.7	37.0	46.1
Section 4	48.0	37.5	43.1
Section 5	50.0		
Current by Section (milliamps)			
Section 1	670	1,275	300
Section 2	1,425	1,932	400
Section 3	840	3,262	1,900
Section 4	1,800	4,925	2,950
Section 5	2,325		

Results

Table 2 contains the penetration, opacity, and emissions results estimated by ESPMGEMS, ESPMOLD, and SORI for the three ESP data sets. The table also shows the actual measured values of penetration, opacity, and emissions. As can be seen, each program generally predicted acceptable results, as compared with the measured results. Results are considered accurate if the measured value falls between the estimated values of the two different non-ideal parameter sets. Each program estimated efficiency and emissions more accurately than opacity.

Figures 1-3 show comparisons of the penetration results obtained from the Very Detailed calculation mode of the three models. These are the figures that should be used for model performance comparisons, since this is the mode most likely to be used for final decisions by utility personnel. Figures 4-12 illustrate the penetration results obtained from the different calculation modes of each model with each ESP. As shown in these figures, each model usually predicted accurate penetrations for at least one calculation mode for each ESP.
Of the three models tested, ESPMGEMS is the most user-friendly for data entry. The menu driven software is simple to follow and the screens are pleasing to the eye. SORI and ESPMOLD are also menu-driven, but the displays not as advanced. However, for running calculations, ESPMOLD is the most straight forward. ESPMOLD offers calculation modes which are not too complex and are easy to access from the main menu. ESPMGEMS has number of calculation modes and auxiliary programs which may be confusing to the inexperienced user. In addition to the four calculation modes previously described, ESPMGEMS contains several auxiliary programs which calculate missing data and fine tune the performance. The calculation modes of SORI are easy to follow, but in order to access them, the user must exit the data entry program and run a separate calculation program.

It was expected that the Very Detailed mode should be the most accurate when compared to field results. However, the evaluation demonstrated that this is not necessarily the case.

ESP 1

ESP 1 is the largest and most efficient (according to measured results) of the three ESPs used in this study. As seen in Table 2, each model correctly predicted ESP 1 to be the most efficient of the three ESPs. The efficiency was estimated reasonably by at least one calculation mode of each of the models. However, ESPMOLD was the only model which accurately predicted efficiency using all three modes. ESPMGEMS accurately predicted efficiency with the Standard, Rapid, and Detailed modes, and overestimated it with the Very Detailed mode. SORI underestimated the efficiency in the Very Detailed mode and accurately predicted it with the Rapid mode.

The emissions were estimated reasonably by at least one calculation mode of each of the models. As with the efficiencies, ESPMOLD correctly predicted the emissions with all three modes and ESPMGEMS accurately predicted them with every mode except Very Detailed. The Rapid mode of SORI correctly predicted emissions, and the Very Detailed mode overestimated them.

Table 2.
Comparison of ESP Results for Three Different Data Sets Using ESPMGEMS, ESPMOLD, and SORI

		ESPMGEMS				ESPMOLD			SORI	
	MEASURED	Standard	Rapid	Detailed	Very Detailed	Rapid	Detailed	Very Detailed	Rapid	Very Detailed
ESP 1										
(Sneakage=0.05, Sigma=0.15)										
Efficiency (%)	99.58	99.58	99.58	99.67	99.79	99.63	99.64	99.63	99.76	99.40
Opacity (%)	3.0	9.7	9.5	7.5	4.8	6.5	6.2	6.3	6.0	14.4
Emissions (lb/MBtu)	0.011	0.010	0.010	0.008	0.005	0.009	0.009	0.009	0.007	0.017
(Sneakage=0.10, Sigma=0.25)										
Efficiency (%)	99.58	99.36	99.40	99.51	99.66	99.40	99.41	99.40	99.57	99.07
Opacity (%)	3.0	11.4	11.2	9.1	6.1	9.6	9.3	9.4	9.6	19.7
Emissions (lb/MBtu)	0.011	0.016	0.015	0.012	0.008	0.014	0.014	0.014	0.012	0.026
ESP 2										
(Sneakage=0.05, Sigma=0.15)										
Efficiency (%)	98.77	99.53	98.65	98.64	98.82	98.02	98.76	98.76	99.13	98.90
Opacity (%)	NA	11.6	28.5	28.7	25.9	30.9	21.7	21.8	19.5	23.2
Emissions (lb/MBtu)	0.042	0.016	0.051	0.052	0.045	0.075	0.047	0.047	0.031	0.040
(Sneakage=0.10, Sigma=0.25)										
Efficiency (%)	98.77	99.65	98.21	98.18	98.40	97.54	98.36	98.37	98.70	98.40
Opacity (%)	NA	15.5	30.6	30.9	28.1	34.1	25.1	25.2	23.6	27.3
Emissions (lb/MBtu)	0.042	0.012	0.068	0.069	0.061	0.093	0.062	0.062	0.045	0.057
ESP 3										
(Sneakage=0.05, Sigma=0.15)										
Efficiency (%)	98.44	97.98	98.55	98.77	99.06	98.90	98.85	98.84	98.80	97.30
Opacity (%)	15.0	23.0	19.8	17.0	13.2	11.0	10.9	11.1	17.1	32.6
Emissions (lb/MBtu)	0.035	0.042	0.030	0.026	0.020	0.022	0.023	0.023	0.023	0.051
(Sneakage=0.10, Sigma=0.25)										
Efficiency (%)	98.44	97.35	98.06	98.31	98.67	98.37	98.33	98.32	98.20	96.40
Opacity (%)	15.0	25.6	22.4	19.6	15.6	14.9	14.6	14.8	22.0	37.9
Emissions (lb/MBtu)	0.035	0.056	0.041	0.035	0.028	0.032	0.033	0.033	0.033	0.066

None of the models accurately estimated opacity for ESP 1. All of the predicted values of opacity for each mode were at least 100 percent higher than the measured opacity.

Figure 1 shows that ESPMGEMS underestimated penetration in the Very Detailed calculation and SORI overestimated it. Figures 4-6 illustrate ESP 1 penetration results obtained from each model. ESPMGEMS estimated ESP 1 to have a lower penetration as the degree of detail in the calculations increased, with the exception of the Standard mode. The Rapid mode of ESPMGEMS predicted conservative efficiencies and the Very Detailed mode predicted more aggressive efficiencies. The penetrations predicted by SORI followed a pattern opposite to that demonstrated by ESPMGEMS (see Figure 6). The Very Detailed mode predicted a much higher penetration than Rapid. ESPMOLD produced accurate results using every calculation mode, but the results were very similar for each mode; the penetrations differ only by one hundredth of a percent.

ESP 2

According to actual measured values, ESP 2 is the second most efficient ESP of the three used in this comparison. SORI is the only model which predicted this, as shown on Table 2. The Very Detailed calculation mode of ESPMGEMS and ESPMOLD estimated that it is the least efficient. ESPMGEMS accurately estimated efficiency with the Very Detailed calculation mode only. The other modes of ESPMGEMS underestimated the efficiency, with the exception of the Standard mode which greatly overestimated it. It should also be pointed out that the Standard mode predicted a higher efficiency with the larger sneakage and sigma values. Theoretically, such a result is impossible and this pattern was not predicted in any of the other configurations. ESPMOLD estimated efficiencies that were nearly accurate (within one hundredth of a percent) with the Detailed and Very Detailed modes and underestimated it with the Rapid mode. SORI predicted accurate efficiencies with both modes.

ESPMGEMS overestimated the emissions with the Rapid, Detailed, and Very Detailed calculation modes, and underestimated them with the Standard mode. ESPMOLD overestimated emissions with all calculation modes. SORI accurately estimated emissions with both modes.

Since the measured value of opacity for ESP 2 was not available, it is not known how accurate the models predicted opacity.

As shown in Figure 2, all three models predicted similar results of penetration with the Very Detailed mode. Figures 7-9 illustrate the penetration results predicted by the models. Figure 7 shows that the Very Detailed mode of ESPMGEMS estimated a lower penetration than the Rapid mode. The Standard mode predicted a penetration much lower than the other modes. As with ESP 1, the efficiency estimated by SORI was greater with Rapid than Very Detailed for ESP 2, see Figure 9. ESPMOLD produced very similar results with the Detailed and Very Detailed modes, Figure 8.

ESP 3

ESP 3 is the least efficient ESP, according to actual measured values. SORI is the only model which predicted this, as seen in Table 2. ESPMGEMS underestimated efficiencies with the Standard mode, overestimated them with the Very Detailed mode, and accurately predicted them with the Rapid and Detailed modes. ESPMOLD is the only model which accurately estimated the efficiency in all three calculation modes. SORI accurately predicted the efficiency with the Rapid mode and underestimated it in the Very Detailed mode.

Emissions were only predicted accurately by the Rapid and Detailed modes of ESPMGEMS. The Very Detailed mode of ESPMGEMS underestimated the emissions and the Standard mode overestimated them. ESPMOLD underestimated emissions with all modes and SORI overestimated them with the Very Detailed mode and underestimated them with the Rapid mode.

ESPMGEMS predicted accurate estimates of opacity with the Very Detailed mode and overestimated it with the other modes. ESPMOLD produced a reasonable estimate of opacity for all three modes, and SORI greatly overestimated it.

Figure 3 shows that ESPMOLD is the only model which accurately estimated penetration of ESP 3 using the Very Detailed calculation mode. Figures 10-12 graphically illustrate penetration results for ESP 3. Again it can be seen that SORI estimates a higher penetration with the Very Detailed mode than the Rapid mode, and ESPMGEMS predicts a lower penetration with the Very Detailed mode. In general, the Rapid and Detailed modes of ESPMGEMS appear to be the most accurate. The results from the different calculation modes of ESPMOLD were all very similar.

Conclusions and Observations

From Table 2, it can be seen that all three models produced reasonable results. None of the models proved to be much more accurate than the others, although some general observations were made which are discussed below.

It was expected that the Rapid calculation modes of the models would be the least accurate and the Very Detailed mode would be the most accurate. The Very Detailed modes of the models seemed to predict results which were no more accurate than those of the other modes. However, the results of the different calculation modes seemed to follow a pattern. As illustrated in Figures 4, 7, and 10, with the exception of the Standard mode, the penetrations estimated by ESPMGEMS decreased as the complexity of the calculation mode increased. ESPMGEMS predicted the greatest penetration using the Rapid mode for all three ESPs, followed by the Detailed mode, then the Very Detailed mode. This order was reversed with SORI; Figures 6, 9, and 12. The figures indicate that ESPMGEMS may tend to underestimate efficiency in the Rapid mode and overestimate it in the Very Detailed mode. The opposite is true for SORI. SORI is conservative in the Very Detailed mode. The ESPMOLD penetration results, Figures 5, 8, and 11, were very similar between calculation modes, particularly Detailed and Very Detailed, and generally fell in between the results from the other two models.

Another interesting observation is that the models did not predict the ESPs to follow the same order of increasing efficiencies, as seen in Table 2. The measured results show that ESP 1 is the most efficient ESP, followed by ESP 2, with ESP 3 being the least efficient. All of the models predicted ESP 1 to be the most efficient. SORI predicted the correct pattern for both Rapid and Very Detailed modes. The Rapid and Standard modes of ESPMGEMS predicted that ESP 2 was more efficient than ESP 3, but the Detailed and Very Detailed modes of ESPMGEMS predicted that ESP 3 had a higher efficiency than ESP 2. The Rapid mode of ESPMOLD predicted that ESP 2 was less efficient than ESP 3. The Detailed and Very Detailed modes also predicted this for the first set of non-ideal conditions, but predicted the opposite with the second set.

Summary

ESPMGEMS produced reasonable results of ESP performance simulation for all three data sets studied. Accurate efficiencies were estimated by at least one of the model's calculation modes for all three ESPs. The model also predicted reasonable estimates of emissions for two of the ESPs and of opacity for one of the two ESPs which had actual opacity data available. The performance results were not significantly more or less accurate than those produced by ESPMOLD and SORI. However, of the three models, ESPMGEMS is the most user-friendly and the easiest to operate. It also contains several auxiliary models and correlations which can be very beneficial. We believe it will be a useful tool for ESP performance evaluation, ESP modification assessment, and fuel switching analysis.

Acknowledgements

The work for this project was performed under EPRI sponsorship with the guidance of EPRI project manager, Dr. Ralph Altman. Dr. Phil A. Lawless of RTI is the program's developer. SAI would like to thank Dr. Altman and Dr. Lawless for their continued support and cooperation.

References

1. *Precipitator Performance Estimation Procedure.* Palo Alto, California: Electric Power Research Institute, February, 1987. CS-5040.

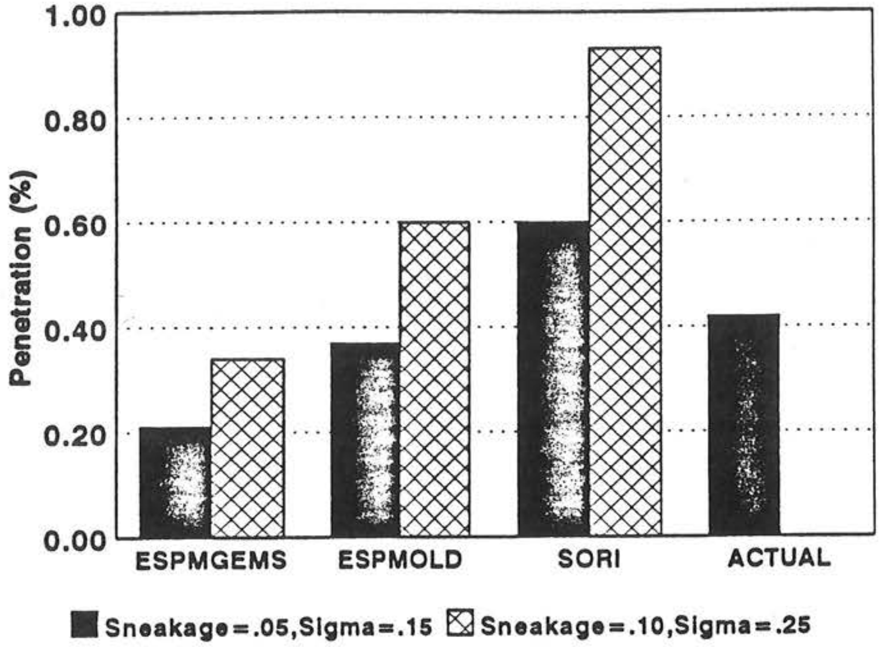

Figure 1: Comparison of Penetration Results for ESP 1 Using Very Detailed

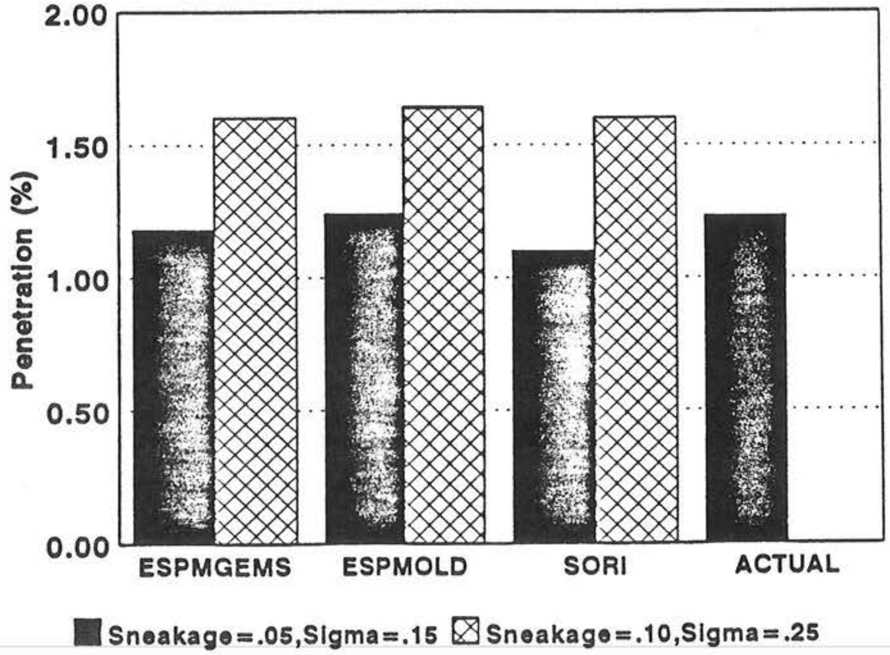

Figure 2: Comparison of Penetration Results for ESP 2 Using Very Detailed

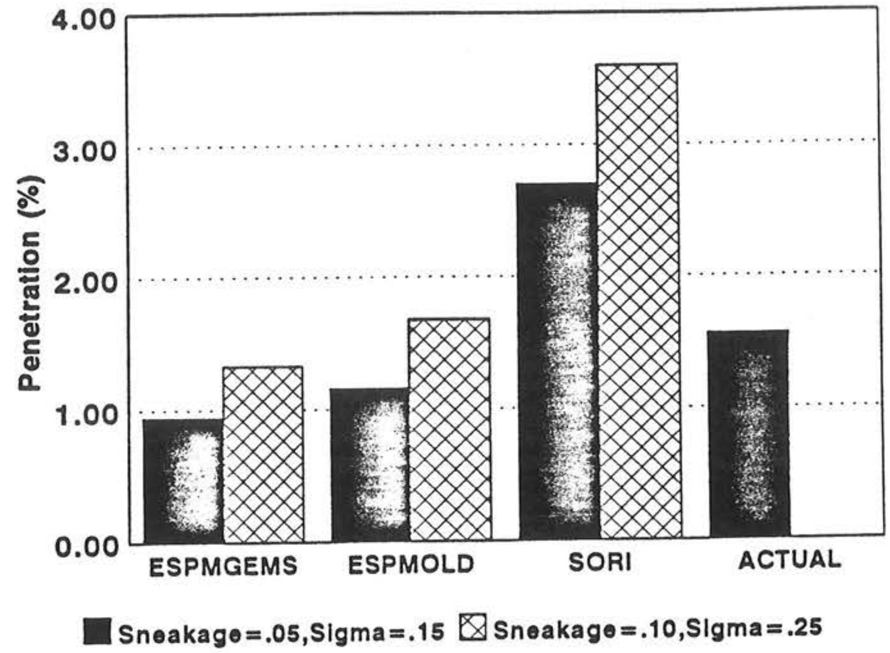

Figure 3: Comparison of Penetration Results for ESP 3 Using Very Detailed

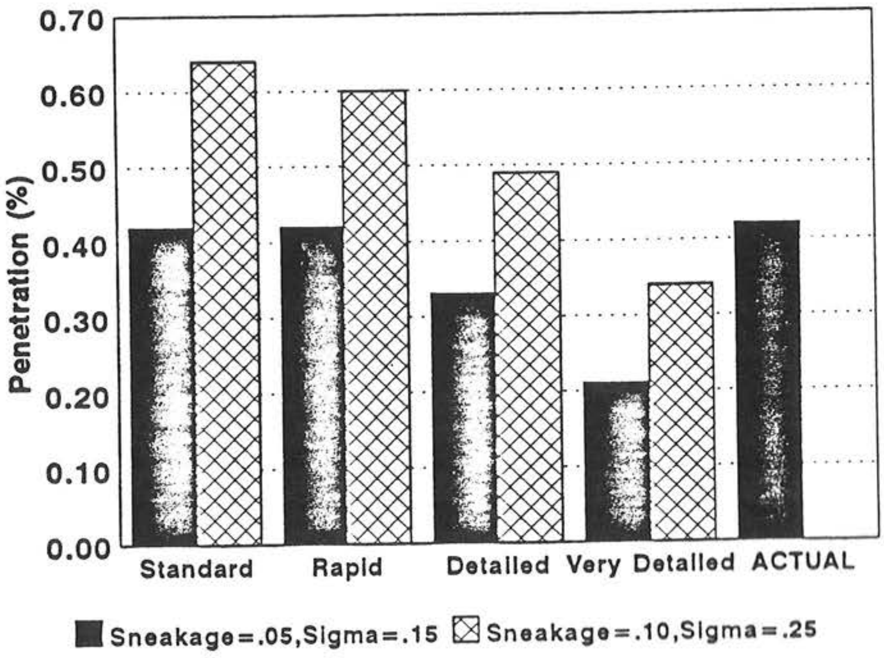

Figure 4: Penetration Results for ESP 1 Using ESPMGEMS

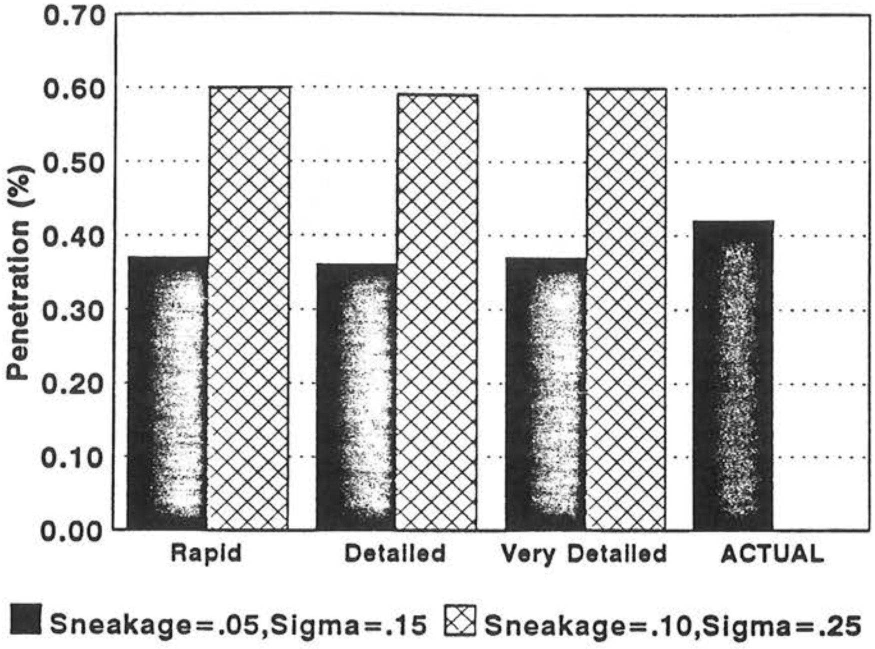

Figure 5: Penetration Results for ESP 1 Using ESPMOLD

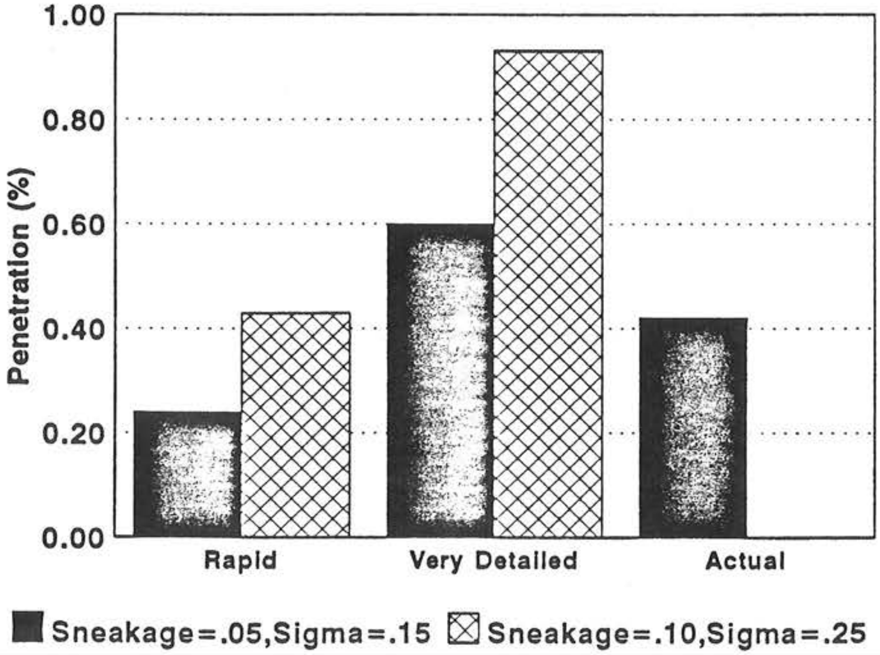

Figure 6: Penetration Results for ESP 1 Using SORI

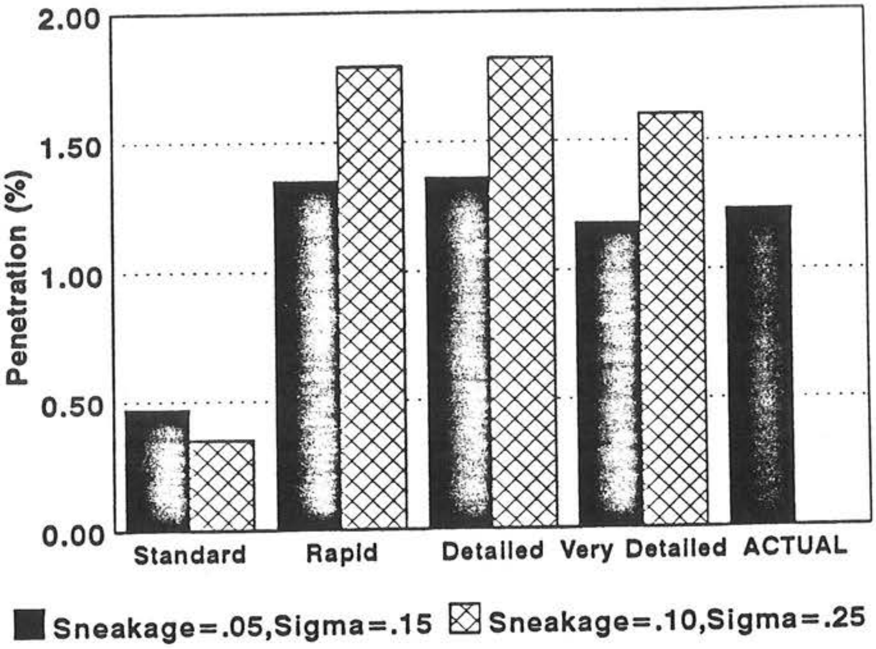

Figure 7: Penetration Results for ESP 2 Using ESPMGEMS

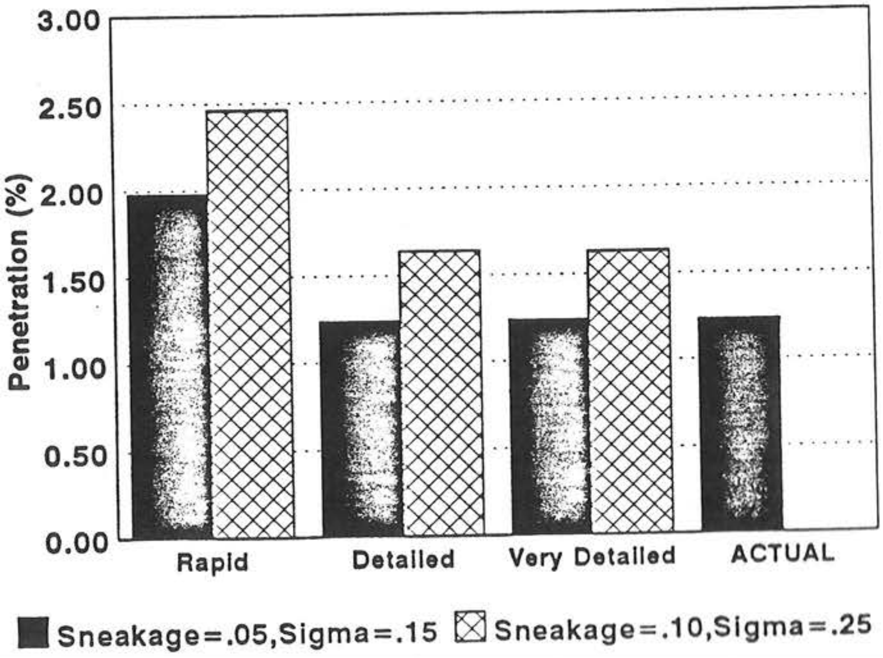

Figure 8: Penetration Results for ESP 2 Using ESPMOLD

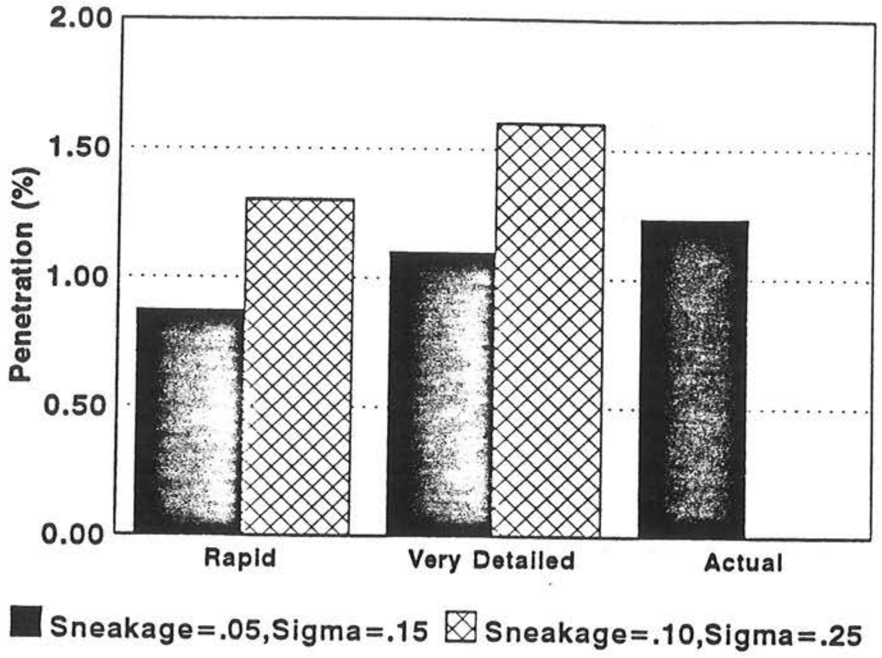

Figure 9: Penetration Results for ESP 2 Using SORI

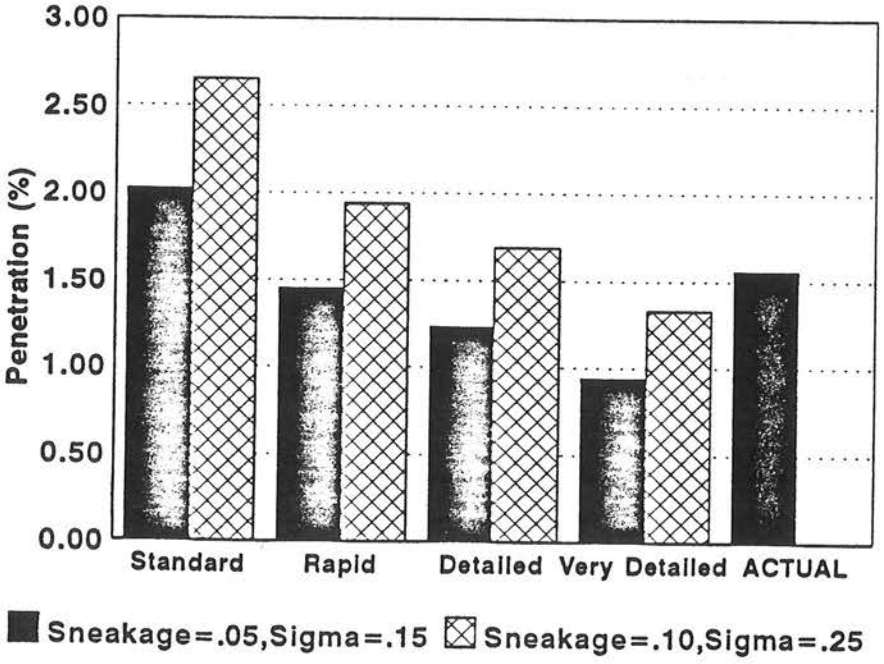

Figure 10: Penetration Results for ESP 3 Using ESPMGEMS

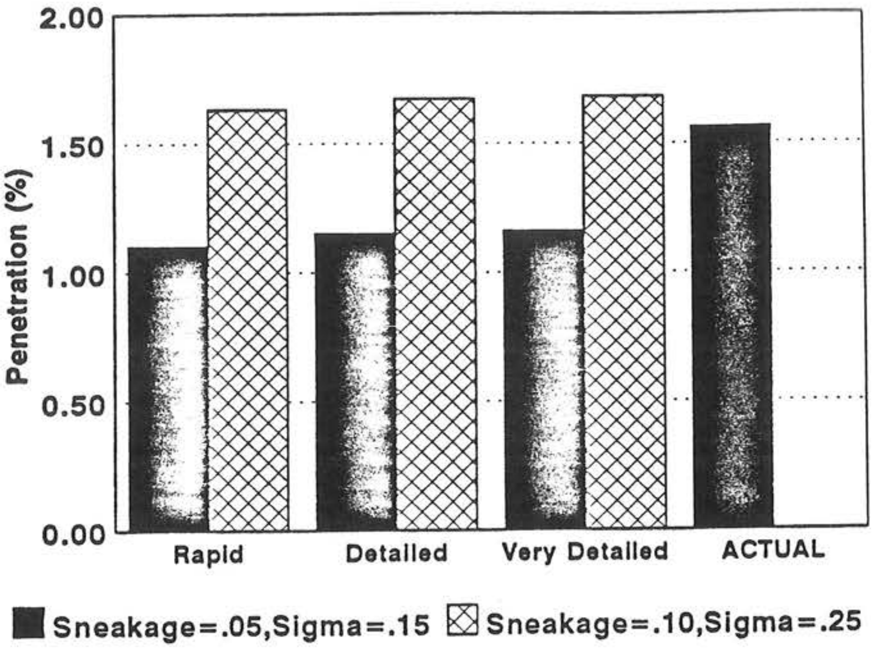

Figure 11: Penetration Results for ESP 3 Using ESPMOLD

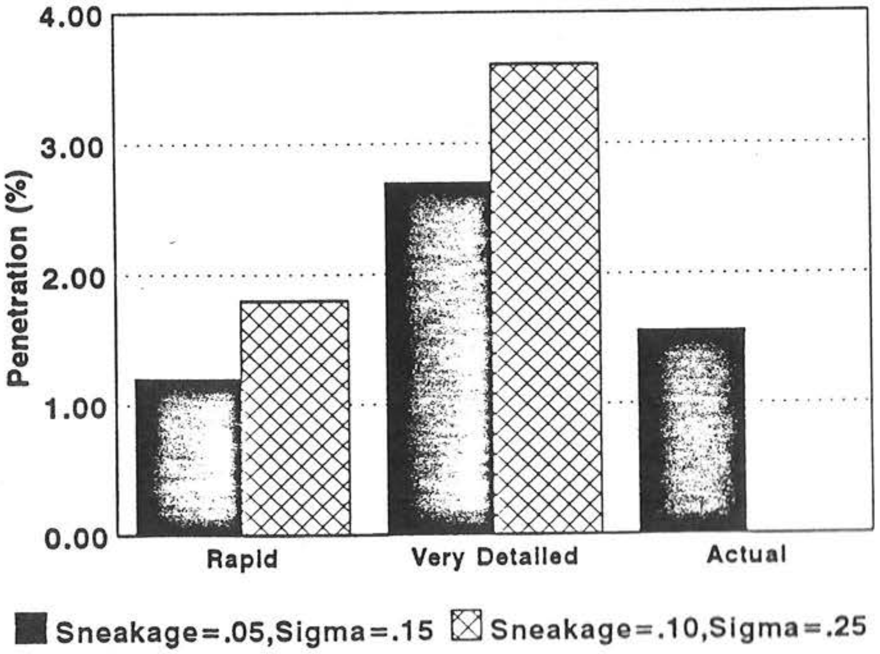

Figure 12: Penetration Results for ESP 3 Using SORI