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IMPROVED ELECTROSTATIC PRECIPITATOR PERFORMANCE BY USE OF FLUE GAS CONDITIONING AGENTS

PHASE III

THE EFFECT OF THREE CONDITIONING AGENTS AND COAL BLENDING ON THE ELECTRICAL RESISTIVITY AND ELECTROSTATIC PRECIPITATION OF FLY ASH FROM LUSCAR COAL

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January 1978

ENERGY RESEARCH PROGRAM

Energy Research Laboratories
ERP/ERL 78-17 (IR)

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by

T. D. Brown* and G. K. Lee**

ABSTRACT

A pilot-scale (75 kg/h) boiler equipped with a two-stage electrostatic precipitator has been used in a combustion investigation of the effects of ammonium sulphate, sodium sulphate and triethylamine injection on fly-ash resistivity and electrostatic precipitator efficiency.

Injection of these conditioning agents into the combustion products of Luscar coal at flue-gas temperatures of 300°C produced, in all cases, a reduction in fly-ash resistivity from the base level of 4.2×10^{11} ohm cm. In the case of ammonium sulphate injection across the concentration range 0.1 to 1.3 g/kg coal the continuous reduction in fly-ash resistivity to 5×10^{8} ohm cm was accompanied by a continuous reduction in precipitator efficiency from 76% to 40%. With sodium sulphate injection across the concentration range 1 to 7 g/kg coal the reduction in fly-ash resistivity to 1×10^{9} ohm cm was accompanied by an increase in precipitator performance to 82% at injection rates above 4 g/kg coal. With triethylamine injection across the concentration range 1.5 to 4 g/kg coal the observed continuous reduction in fly-ash resistivity to 5×10^{9} was accompanied by a continuous increase in precipitator efficiency to 92.3%. In these experiments a strong residual ("memory") effect was recorded after triethylamine injection had stopped.

Blending the Luscar coal with a Pennsylvanian bituminous coal produced a linear reduction in fly-ash resistivity with reduced mass fraction of the Luscar coal. A maximum precipitator efficiency of 96% was recorded with the 50:50 blend at which ratio the fly-ash resistivity was 3×10^{9} ohm cm.

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INTRODUCTION

A joint research project between Ontario Hydro and the Canadian Combustion Research Laboratory (CCRL) was initiated in October 1975 to investigate the potential of various methods of conditioning fly ash to enhance the performance of electrostatic precipitator when burning low sulphur coals. Carried out under a component part of the Canada Centre for Mineral and Energy Technology (CANMET'S) Energy Research Program (ERP), which deals with the increased utilization of Canadian coals, the project embraced three phases:

Phase I demonstrated that the CCRL pilot-scale research boiler was capable of producing a fly ash with a combustible content of less than 5% and a fly-ash resistivity of greater than 10^{10} ohm cm when Luscar coal was burned with 3% O_2 in the flue gas(1). These target conditions duplicated those known to exist in full-scale boilers when precipitator efficiencies were found to decrease dramatically whenever low-sulphur Luscar coal was burnt as a substitute for a medium-sulphur US coal.

Phase II examined the effect of several chemical and physical conditioning agents on both the fly-ash resistivity and the efficiency of a small two-stage electrostatic precipitator. The conditioning agents were temperature, moisture, sulphuric acid, sulphamic acid, ammonia and sodium sulphate(2).

This report presents the results of the third and final phase of the project during which three additional chemical conditioning agents (ammonia sulphate, sodium sulphate and triethylamine) and the addition of three different amounts of a 2.5% sulphur US coal were studied with respect to electrical resistivity and electrostatic precipitator performance.

THE PILOT-SCALE RESEARCH BOILER

The pilot-scale research boiler, illustrated in Figure 1, was used for the series of combustion trials described herein. The adiabatic combustion zone described previously (2) ensured that the pulverized Luscar coal, which was only moderately reactive, was ignited and largely burned out prior to the flame being subjected to any significant thermal load.

The following boiler operating procedure was used for all tests:

1. At 0500 h, the cold boiler was fired up on No. 2 fuel oil and was allowed to stabilize at full steaming rate and pressure. All continuous monitoring instruments were put into service.
2. At 0730 h, the pulverized coal feed was started with the specified classifier speed and mill temperature. One oil torch was left in operation.
3. At 0830 h, the oil torch was removed and the boiler was operated on pulverized coal only.
4. At 1000 h, the furnace temperatures and the carbon contents of the fly ash had equilibrated and the test measurements were started.
5. By 1500 h, the scheduled test measurements were completed. Between 1500 and 1700 h, repeat measurements were taken if necessary.
6. When all measurements were completed, the fireside surfaces and gas passages downstream of the conditioning agent injection station were water washed and any sintered ash deposits were removed from the furnace bottom.

During each trial the performance parameters measured and the locations of the sampling stations were identical with those used in both Phase I and Phase II of the project.

FUEL AND CONDITIONING AGENT CHARACTERISTICS

Experimental Coals

Washed Luscar coal from western Canada was used throughout the conditioning trials of Phase III. This coal, although ranked as bituminous, had over 30% fusinite and micrinite macerals, both of which are highly oxidized and poorly reactive.

Following completion of the trials with chemical conditioning agents, the Luscar coal was blended with a medium-sulphur Pennsylvania bituminous coal of less oxidized nature. The Pennsylvania coal had a sulphur content of 1.5%, compared with 0.4% for the Luscar coal.

Proximate and ultimate analyses of both coals are given in Table 1.

The Flue-gas Conditioning Agents

The conditioning agents and injection stations used in this phase of the experimental program were:

Conditioning Agent	Dosage Rate g/1000 g coal		Equivalent Gas-Phase Concentration	Injection Point	
				Air Heater Exit	Pulverizer
$(NH_4)_2SO_4$	min	0.1	4 ppm NH_3	x	
	max	1.3	60 ppm NH_3	x	
Na_2SO_4	min	1.0	-	x	x
	max	7.0	-	x	x
$(C_2H_5)_3N$	min	1.5	40 ppm	x	
	max	4	120 ppm	x	

Injection of conditioning agents at the exit from the air heater modified the surface electrical characteristics of the ash particles and allowed a residence time of 3 to 4 seconds between the injection point and the electrostatic precipitator. The injection of sodium sulphate at the pulverizer inlet, which increased this residence time to about 5 seconds, was intended to modify the volume electrical characteristics of the fly ash while passing through the flame.

COMBUSTION PERFORMANCE

Combustion Efficiency

The carbon content of the fly ash during experiments with Luscar coal remained consistently below 2.5% at the operating level of 5% O_2 in the flue gas. No systematic changes occurred throughout the experimental period. During experiments with the coal blends a progressive increase in the carbon content of the fly ash from 2 to 5% was recorded as the proportion of US coal was increased from 0 to 75%. This is in agreement with the generalization that a coal with a low organic oxygen content will require a finer pulverizer grind than a lower rank fuel with a high organic oxygen content(3).

The Effect of Carbon on Fly-ash Resistivity

During Phase II of the program the normal fly ash from Luscar coal was found to have a mean resistivity of 4.22×10^{11} ohm cm at a mean carbon content of 3.2%. This resistivity condition was duplicated in Phase III during which baseline measurements of resistivity were made; the mean value of these measurements was 4.19×10^{11} ohm cm at a mean carbon content of 2.1%.

To determine the influence of combustion efficiency on fly-ash resistivity, the carbon content of the fly ash was increased above the baseline level by reducing the amount of excess combustion air. The number of resistivity measurements was limited by the amount of available coal but the results shown in Table 3 and Figure 2 indicate a step reduction in resistivity at approximately 3.5% carbon in fly ash. The Phase I and Phase II results, which are superimposed on the Phase III results in Figure 2, showed a similar step change at approximately 7.5% carbon in fly ash. Since the same coal was used in all three phases the difference between the critical carbon levels can be attributed to changes in the particle size distribution and consequent packing density as postulated by Sekhar(4), who identified a critical carbon content in isothermal resistivity studies with coal ash and activated carbon.

The fly-ash sampling system used in all phases of the experimental program divides the sample into three size fractions which are given the laboratory classifications "fine", "medium" and "coarse". In this sampling system, the coarse fraction is collected in the main barrel of a cyclone, the medium fraction on retaining grids in the central exhaust tube of the cyclone and the fine fraction on a fibre-glass filter downstream of the cyclone. Typical size distribution of the fly ash collected during Phase I and III (Table 3) shows that the higher critical carbon level is associated with the coarse component of the fly ash, which in all cases had the highest mass fraction and the highest carbon contnet.

These data indicate, therefore, that a predominance of small particles in the fly ash gives the best probability of producing an electrically conducting path through the resistivity sample.

EFFECTS OF CONDITIONING AGENTS ON FLY-ASH RESISTIVITY

Ammonium Sulphate

The effect of ammonium sulphate injection on fly-ash resistivity is shown in Figure 4. The fly-ash resistivity decreased exponentially from 4.2×10^{11} to 4.1×10^{8} ohm cm as the $(NH_4)_2SO_4$ injection rate was increased from zero to 62 ppm equivalent NH_3*. At injection rates up to 182 ppm equivalent NH_3 the resistivity remained constant at 4.1×10^{8} ohm cm. The equation derived from the data to represent this behaviour is shown below:

$$\left[\frac{\log R - \log R_{(sat)}}{\log Ro - \log R_{(sat)}}\right] = 0.7554\, e^{-0.0512(c)}$$

*Equivalent NH_3 is the concentration of ammonia produce by the conditioning agent assuming complete dissociation without subsequent reaction or re-association.

Sodium Sulphate Injection at the Air Heater Outlet

The effect of sodium sulphate injection at the air heater outlet on fly-ash resistivity is shown in Figure 5. At injection rates between zero and 6 g Na_2SO_4/1000 g coal, the resistivity generally decreased from the base level of 4.2×10^{11} to 7.9×10^{8} ohm cm. Injection rates of about 1 g Na_2SO_4/1000 g coal slightly increased the resistivity from the base level to 1.2×10^{12} , however, this is thought to be due to random scatter in the experimental data.

The results indicate that the effect of sodium sulphate on fly-ash resistivity was dependent only on the mass ratio of additive to fuel and was unaffected by the concentration of the aqueous solutions.

Sodium Sulphate Addition to the Coal Feed

The effect of sodium sulphate addition at the pulverizer on fly-ash resistivity is shown in Figure 6. At injection rates between zero and 7 g Na_2SO_4/1000 g coal, the resistivity continuously decreases from the base level of 4.2×10^{11} to 2.3×10^{10}. No evidence of an increase in fly-ash resistivity was recorded at the lowest injection rate of 1.1 g Na_2SO_4/1000 g coal.

The data closely overlap those obtained when sodium sulphate solution was injected into the combustion products, except at the highest injection rate of 7 g Na_2SO_4/1000 g coal. This anomaly can be attributed to partial retention of Na_2SO_4 in the pulverizer at the highest injection rates. An examination of the pulverizer at the end of this trial revealed a build-up of fine coal in a matrix of Na_2SO_4 on the central core of the unit. It is possible that the large volumes of additive solution, associated with high injection rates, resulted in the adhesion of wetted coal particles to hot pulverizer components. The injection rates quoted, which were calculated from input flow rates, are therefore nominal. The effective injection rate was necessarily lower, particularly at the high injection rates.

The results indicate that the effect of sodium sulphate on fly-ash resistivity was independent of the injection location and that it is not necessary for the additive to pass through the flame zone to effectively reduce the fly-ash resistivity. This result agrees with the conclusion reached in Phase II when sodium carbonate was used as a conditioning agent at the same two injection locations.

Triethylamine

The effect on fly-ash resistivity when triethylamine was injected as an aqueous solution at the exit from the air heater is shown in Figure 7. The injection rate, which has been reported as "equivalent $(C_2H_5)_3N$", has been calculated from the measured injection rates and flue gas velocities assuming no dissociation or decomposition of the triethylamine. Figure 7 shows that across the concentration range investigated,the fly-ash resistivity was essentially constant at approximately 3×10^9 ohm cm. This represents a reduction of two orders of magnitude from the base level of 4×10^{11} ohm cm.

There is some evidence of a continued decrease in resistivity as the triethylamine injection rate increased but this is masked by the scatter in the data. The results are analogous to those reported earlier(2),using ammonia as a conditioning agent,when it was observed that injection rates across the concentration range 4 ppm to 140 ppm equivalent NH_3 produced an essentially constant resistivity.

The Triethylamine "Memory" Effect

One singular characteristic of triethylamine was its capacity to maintain ash resistivity values below 10^{11} ohm cm for 16 hours after injection was stopped. With all other conditioning agents, including those used in Phase II, stopping the injection produced an instantaneous reversion of the fly-ash resistivity to its baseline level.

This unique memory effect of triethylamine persisted even after the boiler fireside surfaces were water washed. The injection of sulphuric acid into the combustion products resulted in a further reduction in resistivity followed by reversion to the baseline resistivity value. A subsequent experiment duplicated both the memory effect and its elimination by sulphuric acid injection. Abstracts from the operating log for the period of the experiments with triethylamine are given in Tables 4 and 5.

Is is postulated that the triethylamine was adsorbed on the metallic surfaces of the system and was re-evaporated and adsorbed on gas-borne fly ash to such an extent that the fly-ash resistivity was reduced. This surface adsorption was not affected appreciably by water washing the boiler surfaces. During the period when the memory effect was apparent the equivalent triethylamine concentration could not be measured. It can reasonably be assumed to be extremely low (less than 5 ppm). Under these conditions the fly-ash resistivity was between 10^{10} and 10^{11} ohm cm.

THE EFFECT OF COAL BLENDING ON FLY-ASH RESISTIVITY

The analyses of the two coals used in the coal blending experiments are given in Table 1. Prior to each 16 hr combustion trial, both coals were crushed to less than $\frac{1}{4}$ in., proportioned as specified and then blended in a rotary riffle. The analyses of the blended coals are given in Table 1 and the effect of the different blends on fly-ash resistivity is shown in Figure 8. Over the range 100 to 25% Luscar coal the resistivity decreased linearly with decreases in the mass fraction of Luscar coal. The results for the 100% US coal were too widely scattered to draw a clear conclusion on its resistivity.

PILOT-SCALE ELECTROSTATIC PRECIPITATOR PERFORMANCE

Untreated Fly Ash

To simulate the decrease in full-scale precipitator efficiency which normally occurs when low-sulphur coals are burned as a substitute for medium-sulphur coals, the pilot-scale precipitator was deliberately downgraded to give an efficiency of 75% with untreated fly ash from Luscar coal. This was achieved by minimizing the opportunity for gravity settling within the precipitator and by reducing the effective collection area of the plates.

The resultant mean precipitator efficiency (Table 6)was 76.6% when collecting a fly ash with a mean resistivity of 4.85×10^{11} ohm cm from the untreated Luscar coal.

Ammonium Sulphate

During the use of ammonium sulphate as a conditioning agent across the range 0 to 62 ppm equivalent NH_3 the precipitator efficiency declined continuously from 76.6% to 41% as shown in Figure 9.

This dramatic reduction in precipitator efficiency differs from observations made during Phase II with sulphamic acid, which is another derivative of ammonia and sulphur trioxide. It should be noted that sulphamic acid and ammonium sulphate decompose at 205°C and 530°C respectively. On decomposition they produce, respectively, ammonia plus sulphur trioxide and ammonia plus sulphuric acid. Since both were injected into a flue gas stream at a gas temperature of 300°C the mechanism by which they interact with the fly ash must be different. With sulphamic acid the gaseous decomposition products could be adsorbed on the fly-ash particles. In the case of ammonium sulphate, collision of fly-ash particles with either droplets of dissolved ammonium sulphate or solid ammonium sulphate residues is necessary. These physical collision processes will lead to a less uniform distribution of conditioning agent throughout the fly-ash than can be achieved by a gas adsorption process resulting from the decomposition of sulphamic acid. The effective use of ammonium sulphate will probably require injection into flue gases of temperatures above 530°C.

Sodium Sulphate Injection at the Air-heater Outlet

The effect of sodium sulphate injection at the air-heater outlet on electrostatic precipitator efficiency is shown in Figure 10.

No change in precipitator efficiency was recorded until the addition rate exceeded 4 g Na_2SO_4/1000 g of coal. Above this injection rate the precipitator efficiency increased slightly to 82%.

Sodium Sulphate Addition to the Coal Feed

The addition of sodium sulphate to the coal feed at the pulverizer showed no systematic effect on precipitator efficiency. The results of these trials are shown in Figure 10.

As mentioned previously, the quoted sodium sulphate injection rates during these experiments must be considered as "nominal" because of the sodium sulphate residues found in the pulverizer at the end of the trial. The effective injection rates were thus lower than those calculated from injection flow rates and would produce a smaller change in precipitator performance than that recorded with sodium sulphate injection at the air-heater outlet.

Triethylamine

The injection of triethylamine into the combustion products at the air-heater outlet produced a significant increase in precipitator efficiency. Concentrations of triethylamine in the range 40 ppm to 110 ppm equivalent $(C_2H_5)_3N$ resulted in increases in precipitator efficiency from base level of 76.6% to over 90%. As shown in Figure 11, the precipitator efficiency increased continuously to a maximum efficiency of 93.5% as the injection rate increased to 110 ppm. At the highest injection rate used (120 ppm equivalent $(C_2H_5)_3N$) the precipitator efficiency decreased to approximately 85%. This suggests that injection rates of triethylamine above 110 ppm may adversely affect the precipitation properties of this fly ash.

The Effect of Coal Blending on Pilot-scale Electrostatic Precipitator Performance

The reduced fly-ash resistivity recorded during the experiments with the coal blends was associated with a marked increase in electrostatic precipitator efficiency. The results (Figure 12) show that maximum precipitator efficiency occurred with the 50:50 Luscar blend. The fly-ash resistivity at this blend ratio was 3×10^9 ohm cm.

THE RELATIONSHIP BETWEEN FLY-ASH RESISTIVITY AND ELECTROSTATIC PRECIPITATOR EFFICIENCY

Figure 13 summarizes the experimental data from this Phase of the experimental program. The relationship lines are intended only to show the grouping of data from experiments with different conditioning agents.

In general, the highest precipitator efficiencies were measured when the fly-ash resistivity was between 10^9 and 10^{10} ohm cm. However, resistivities in this range did not inevitably produce high precipitator efficiencies. For example, ammonium sulphate injection reduced electrostatic precipitator efficiency irrespective of the fly-ash resistivity. Clearly, fly-ash resistivity was not the only factor having a significant effect on the efficiency of the pilot-scale precipitator.

EFFECT OF CONDITIONING AGENTS ON PRECIPITATION RATE PARAMETER

A comparison of the effects of the various conditioning agents used in all phases of the flue gas conditioning trials can be made through the use of a normalized precipitation rate parameter.

The calculation of a non-dimensional precipitation rate parameter ratio was mentioned in a previous report(2). However, in view of the importance of the ratio in comparing results from this phase of the program with those reported from Phase II, the development of this ratio will be described.

The efficiency of the pilot-scale precipitator can be described by the generalized Deutsch-Anderson equation:

$$E = 100 \left[1 - \exp \left(\frac{-AW}{V} \right) \right] \qquad (1)$$

where E = Precipitator Efficiency %

A = Specific Collection Area of Plates

V = Volume of Gas Handled

W = Precipitation Rate Parameter

Since, for both phases of the program A and V were constant,

$$E = 100 \left(1- \exp \left(-k . W\right)\right) \qquad (2)$$

If the precipitation rate parameter and the precipitator efficiency in the absence of a conditioning agent are W_o and E_o respectively and the same two parameters in the presence of a conditioning agent (j) at a concentration (c) are W_{jc} and E_{jc} respectively, then Equation (2) above becomes:

$$\exp \ (-kw_o) = \frac{E_o}{100} \qquad (3) \text{ and}$$

$$\exp \ (-kw_{jc}) = \frac{E_{jc}}{100} \qquad (4)$$

Combining equations (3) and (4) yields

$$\frac{W_{jc}}{W_o} = \left[\ln \left(\frac{100 - E_o}{100 - E_{jc}}\right)\right] \cdot \left[\frac{-1}{\ln \ (100 - E_o)}\right] + 1 \qquad (5)$$

The precipitation rate parameter ratio $\frac{W_{jc}}{W_o}$ can be calculated for any experimental condition using the determined values of E_o and E_{jc}.

This method was used to generate the data presented in Figure 14. The only conditioning agent that showed a significant improvement in precipitator efficiency was triethylamine. This improved precipitator efficiency corresponded to a 50% increase in the precipitation rate parameter at injection rates of approximately 110 ppm.

The calculated values of the precipitation rate parameter ratio for the conditioning agents which produced improvement in precipitator performance in both phases of the project are shown in Figure 15. The organic acid conditioning agents (SO_3, H_2SO_4) produced more than a two-fold increase in the precipitation rate parameter whereas the two organic amino-compounds NH_2SO_2OH and $(C_2H_5)_3N$ produced an increase of less than 50%.

The extrapolation of the normalized precipitation rate parameter from pilot-scale results to full-scale practice was described in an earlier report (2).

THE EFFECT OF THE CONDITIONING AGENTS ON FLY-ASH CHARACTERISTICS

Samples of fly ash collected isokinetically at the inlet and outlet of the precipitator were digested in cold distilled water and the pH and water soluble ion concentrations in the extract were determined by standard laboratory techniques. The results of these analyses are presented in Table 7.

Ammonium Sulphate

Using the ammonium sulphate conditioning agent, the water soluble components of the fly ash did not show a consistent variation as the concentration of conditioning agent increased. Injection at concentrations above 3.5 ppm equivalent NH_3 were required to produce detectable levels of water soluble sulphate in the fly ash. These levels were not simply related to the injection rate.

Sodium Sulphate

The injection of sodium sulphate into the combustion products at the exit from the air heater produced a systematic effect on the water-soluble sodium and water-soluble sulphate content of the fly ash entering the pilot-scale precipitator. This is illustrated in Figures 10 and 17. These two figures confirm that only a portion of the sodium sulphate injected at the pulverizer had been entrained in the coal feed to each burner and that the composition of the fly-ash had been only marginally modified during these experiments. Figure 18 illustrates the near-linear relationship between the water soluble conditioning agent ions in the fly-ash and the fly-ash resistivity during all the experiments with sodium sulphate. The mean value of the water soluble $Na:SO_4$ ionic ratio in the fly ash (shown in Table 7) was 1.7 compared to a value of 2 for sodium sulphate. This indicates an essentially uniform pick-up of both ions by the fly ash with some sulphate contribution from the sulphur in the coal.

During experiments with sodium sulphate injection into the pulverizer the ionic ratio ($Na:SO_4$) varied widely. At low nominal injection rates the ratio was close to unity implying that more than one half of the injection sodium which reached the flame did not appear in the fly ash at the precipitator entry. It must therefore have been retained in the boiler deposits. At higher nominal injection rates the ionic ratio ($Na:SO_4$) was 5.8 and 2.8.

Throughout all the experiments with sodium sulphate the water soluble sodium and sulphate ions were concentrated in the finest fractions of fly ash which constituted about 60% of the total fly ash.

Triethylamine

During the experiments with triethylamine the water soluble material in the fly ash increased from a base level of 6% up to 18% at the maximum injection rate of 120 ppm equivalent $(C_2H_5)_3N$ and the pH of the water extract remained in the range 6.5 to 7.5.

Fly Ash at the Precipitator Outlet

The analyses of the fly-ash at the precipitator outlet during the experiments with the conditioning agents and the coal blends are shown in Tables 8 to 11 inclusive.

The fly ash emissions during experiments with $(NH_4)_2SO_4$ contained a maximum of 1.3% water soluble sulphate with the pH of the water extract being consistently between 6.2 and 7.

The injection of Na_2SO_4 into the combustion products gave fly-ash emissions in which the water soluble sulphate increased to a maximum of 14% and the water soluble sodium increased to 17%. The addition of Na_2SO_4 to the fuel gave fly-ash emissions in which the water soluble sulphate increased to 1% and the water soluble sodium to 2%. This is thought to reflect the retention of Na_2SO_4 in the pulverizer.

CONCLUSIONS

The mean electrical resistivity of the fly ash produced from Luscar coal during these experiments was 4.2×10^{11} ohm cm at a mean carbon content of 3.2%. This carbon content was below the threshold level - approximately 4% - above which the presence of carbon was shown to reduce markedly the fly-ash resistivity. At this baseline resistivity value the mean efficiency of the pilot-scale electrostatic precipitator was 76.6%.

The three chemical conditioning agents used (ammonia sulphate, sodium sulphate and triethylamine) all reduced the fly-ash resistivity. However, these reductions in resistivity were not necessarily accompanied by an increase in precipitator efficiency.

Ammonium sulphate produced an exponential decrease in resistivity to 5 x 10^8 ohm cm as the addition rate was increased to 60 ppm equivalent NH_3. This was accompanied by a continuous reduction in precipitator efficiency to 40% at an equivalent NH_3 concentration of 60 ppm.

Sodium sulphate injection into the flue gases produced a continous reduction in resistivity to 1 x 10^9 ohm cm as the injection rate was increased to 6 g/kg fuel. This was only accompanied by an increase in precipitator efficiency at injection rates above 4 g/kg fuel. Sodium sulphate injection into the fuel at the pulverizer produced an exponential reduction in fly-ash resistivity to 5 x 10^{10} ohm cm as the nominal injection rate was increased to 6.5 g/kg fuel. No systematic change in precipitator efficiency was recorded.

Triethylamine produced an exponential reduction in fly-ash resistivity to 5 x 10^9 ohm cm as the injection rate was increased to 120 ppm equivalent $(C_2H_5)_3N$. This was accompanied by an increase in precipitator efficiency to 92.3% at an injection rate of 110 ppm equivalent $(C_3H_5)_3N$.

The difference in fly-ash resistivity during sodium sulphate injection at the alternative locations was largely due to the sodium sulphate being retained in the pulverizer and not reaching the flame.

Triethylamine produced a persistent "memory" effect. Reduced fly-ash resistivities prevailed for up to 16 hours after injection was stopped. Duplication of this effect in utility operation would be a significant benefit since failure of the injection system will not lead to an immediate degradation in precipitator performance.

Blending the Luscar coal with a Pennsylvania bituminous coal produced a linear decrease in fly-ash resistivity from 4.2 x 10^{11} to 1.5 x 10^8 as the proportion of Luscar coal was reduced. This was accompanied by a significant increase in electrostatic precipitator efficiency, a maximum precipitator efficiency of 96% was recorded with the 50:50 blend.

ACKNOWLEDGEMENTS

The assistance and co-operation of the staff of the Canadian Combustion Research Laboratory (CCRL) in the conduct of this research project is gratefully acknowledged. Credit is also due to Mr. N. Sekhar and staff from Ontario Hydro who provided special instrumentation and supported CCRL measurements of fly-ash resistivity.

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TABLE 1

Analyses of the Experimental Coals

	Luscar Coal (as fired)	US Bituminous Coal (as fired)	Blends		
			75% Luscar 25% US	50% Luscar 50% US	25% Luscar 75% US
Moisture	6.30	4.31			
Ash	12.91	9.71			
V.M	31.70	32.70			
Fixed carbon	49.09	53.28			
Carbon	63.41	71.42			
Hydrogen	4.32	5.14			
Sulphur	0.31	2.18	1.04	1.63	2.08
Nitrogen	0.95	1.28			
Oxygen	11.80	5.33			

TABLE 2

Summary of Combustion Conditions

		Luscar Coal	US Coal	Blends 75% Luscar 25% US	 50% Luscar 50% US	 25% Luscar 75% US
Feed Rate	kg/h	69.5 ± 2.5	60.3 ± 3.5	69.6 ± 2.0	65.9 ± 2.5	62.6 ± 2.0
Oxygen Content of Flue Gas	%	4.9 ± 0.2	4.9 ± 0.2	5.0 ± 0.2	5.0 ± 0.2	5.0 ± 0.2
Fly-ash Loading	g/m^3	1.62 ± 0.32	1.37 ± 0.07	1.58 ± 0.16	1.64 ± 0.09	1.57 ± 0.12
Combustible Content of Fly Ash	%	2.16 ± 0.56	4.17 ± 0.89	2.98 ± 0.41	3.68 ± 0.26	5.06 ± 1.00

TABLE 3

Fly-ash Resistivity and Size Distribution in the Critical Carbon Range

	Carbon in Fly Ash %	Fly-ash Resistivity ohm cm	Distribution of Fly-ash in the CCRL Sampling System		
			Fine %	Medium %	Coarse %
Phase II Trials	7.4	1.1×10^7	24.5	22.3	53.0
	7.4	6.2×10^6			
	7.7	2.3×10^7	23.2	23.4	53.4
	8.3	2.7×10^7	27.1	22.0	50.9
Phase III Trials	3.3	4.7×10^8	52.2	28.6	19.2
	3.5	3.0×10^8	74.1	12.2	13.8
	4.0	4.5×10^8	59.6	25.1	15.3

The first four samples were taken during the exploratory combustion trials; the fifth, sixth and seventh samples were taken during the Phase III conditioning trials.

TABLE 4

The Residual Effects of Triethylamine

Date	Time	Operating Log Data	Measured Resistivity ohm cm
19 May 77	0800	Boiler Operating on Luscar Coal	
	1000	No Additive Injection	3.33×10^{11}
	1300	Triethylamine Addition	1.05×10^{10}
	1420	Triethylamine Addition	1.53×10^{10}
	1515	Triethylamine Addition	7.42×10^{9}
20 May 77	0800	Boiler Operating on Luscar Coal	
	0945	Triethylamine Addition	9.79×10^{8}
	1050	Triethylamine Addition	5.89×10^{9}
	1145	Triethylamine Addition	1.04×10^{9}
	1245	Triethylamine Addition	6.64×10^{8}
	1355	Triethylamine Addition	3.46×10^{9}
	1400	No Further Addition	
	1510		2.83×10^{7}
	1615	Boiler Shutdown	
21 May 77 22 May 77 23 May 77		Boiler Shutdown	
24 May 77	0800	Boiler Operating on Luscar Coal No Additive Injection	
	1430	No Additive	4.01×10^{10}
	1600	No Additive	1.24×10^{10}
	1615	System Water Washed	
	1645	Boiler Shutdown	
25 May 77	0800	Boiler Operating on Luscar Coal No Additive Injection	
	1000	No Additive	2.60×10^{10}
	1215	No Additive	9.05×10^{10}
	1300 1330	H_2SO_4 Injection	1.37×10^{9}
	1450	No Additive	3.14×10^{11}

TABLE 5

The Residual Effects of Triethylamine

Date	Time	Operating Log Data	Measured Resistivity ohm cm
26 May 77	0800	Boiler Operating on Luscar Coal Triethylamine Addition	
	1005		7.04×10^9
	1130		9.37×10^9
	1300		3.77×10^9
	1420		4.64×10^9
	1425	No Further Addition	
	1725		5.89×10^9
	1730	H_2SO_4 Addition; 11% at 30 ml/min	
	1800	Boiler Shutdown	
27 May 77	0800	Boiler Operating on Luscar Coal H_2SO_4 Injection; 4% at 30 ml/min	
	0940		1.05×10^{11}
	1000	No Further Injection	
	1110		1.79×10^{11}
	1230		3.6×10^{11}

TABLE 6

Electrostatic Precipitator Efficiency Measurements with Untreated Fly Ash

Fly-Ash Resistivity ohm cm	Precipitator Efficiency %
1.05×10^{12}	78.3
3.25×10^{11}	81.9
3.03×10^{11}	72.4
3.49×10^{11}	77.0
6.35×10^{11}	78.1
3.19×10^{11}	75.1
5.62×10^{11}	78.8
Mean Resistivity 4.58×10^{11} ohm cm	Mean Precipitator Efficiency = 76.6%

TABLE 7

The Effects of the Conditioning Agents on Water Soluble Components in the Fly Ash

Conditioning Agent	Dosage Rate		Water Soluble Component in Fly Ash			Ionic Ratio Na:SO_4
	g/1000g Coal	Equivalent ppm	Total %	Na %	SO_4 %	
$(NH_4)_2SO_4$	0.1	3.6	6.7		0	
	0.4	13.6	8.6		1.9	
	0.6	21.6	8.3		4.7	
	1.3	46.6	7.1		0	
Na_2SO_4 (Injection at Air Heater Outlet)	0.98		13.1	2.2	6.2	1.5
	2.02		21.1	4.9	10.4	2.0
	2.78		23.2	5.0	9.9	2.1
	3.15		29.4	5.0	16.3	1.3
	3.19		22.5	4.1	12.4	1.4
	4.08		23.9	6.3	13.5	1.9
	5.37		35.5	7.0	19.2	1.5
	5.95		28.2	6.4	14.8	1.8
Na_2SO_4 (Addition to Coal Feed)	1.12		3.48	0.6	0	
	2.28		5.46	0.5	1.9	1.1
	2.42		5.99	0.6	1.9	1.3
	3.96		6.71	2.8	2.0	5.8
	6.79		5.76	2.0	3.0	2.8
$(C_2H_5)_3N$	1.4	41.2	7.26		0	
	2.05	60.2	4.83		–	
	2.72	80.1	7.36		0	
	3.94	11.6	12.76		1.71	
	4.01	11.8	18.04		6.40	

TABLE 8

Analyses of Fly-ash at the Precipitator Outlet during $(NH_4)_2SO_4$ Injection

Concentrations of (NH_4) Equivalent NH_3 ppm	pH of Water Extract	Water Soluble Content %	Water Soluble Ions as % of Fly-ash					
			SO_4	Ca	Fe	Mg	K	Na
0	6.4		0	0.3	.1	.2	.1	.2
3.4	7.0	2.3	1.1	0.3	0.08	0.01	0.02	0.11
3.6	6.9	7.1	1.3	0.1	0.8	0.01	0.0	0.14
6.5	6.9	15.0	0	0.3	1.3	0.02	0.0	0.0
13.5								
21.6								
22.9	6.2	3.8	0	1.2	1.4	0.04	0.1	0.3

TABLE 9

Analyses of Fly-ash Escaping the Precipitator Outlet During Na_2SO_4 Injection

Concentration of Na_2SO_4 added g/kg coal	pH of Water Extract	Water Soluble Content %	Water Soluble Ions as of Total Fly-ash					
			SO_4	Ca	Fe	Mg	K	Na
0	6.4		0	3	0.1	0.2	0.1	0.2
1.23	7.76	7.5	3.8	.2	.1	.02	.22	3.05
2.54	7.59	30.4	6.9	.35	0	.03	.01	5.06
3.15		38.6	10.8	.3	.01	.03	.03	8.39
3.19		24.6	7.9	.18	.02	.07	.01	5.28
3.57	7.86	32.4	14.3	.2	.1	.02	.02	17.37
3.90	7.74	38.1	11.1	.1	.1	.02	.02	7.8
4.09		42.9	10.2	.06	.06	.05	.00	6.79
1.12*		21.6	0	.23	.14	.01	.01	.4
2.34*	7.60	11.8	0.8	.60	.02	.04	.03	1.96
2.41*	7.86	50.1	0.6	.09	.02		.02	0.19
3.78*	7.66	11.4	0.7	.25	.03	.01	.02	0.24
8.13*	7.51	15.0	1.0	.41	.03	.03	.02	0.22

*Injection at the pulverizer.

TABLE 10

Analyses of Fly-ash at the Precipitator Outlet during $(C_2H_5)_3N$ Injection

Concentration of $(C_2H_5)_3N$ Equivalent ppm	pH of Water Extract	Water Soluble Content %	Water Soluble Ions as % of Total Fly-ash					
			SO_4	Ca	Fe	Mg	K	Na
0	6.4		0	0.3	0.1	0.2	0.1	0.2
41.8	7.8	31.0	0	.84	0	.06	.03	3.89
60.2	7.70	33.4	0	.78	.11	.07	.03	0.90
80.1				.60	0	.05	.06	1.25
116.4	5.12	40.4	0	0.47	0.78	.16	.04	3.38
118.5			0	1.59	.05	.07	.04	1.23

TABLE 11

Analyses of Fly Ash in the Precipitator Outlet during Experiments With Coal Blends

Blend Ratio Luscar: US	pH of Water Extract	Water Soluble Content %	Water Soluble Ions as % of Total Fly-ash					
			SO_4	Ca	Fe	Mg	K	Na
100 : 0	6.36	15.5	0	3.0	0.1	0.18	0.13	0.19
75 : 25	6.98	71.6	0	1.7	0.05	0.10	0.03	0.08
50 : 50	4.22	76.7	3.6	1.04	0.05	0.08	0.05	0.08
25 : 75	5.12	81.0	0	1.87	0.09	0.18	0.10	0.30
0 :100	5.11	96.2	0	.57	0.03	0.05	0.03	0.07

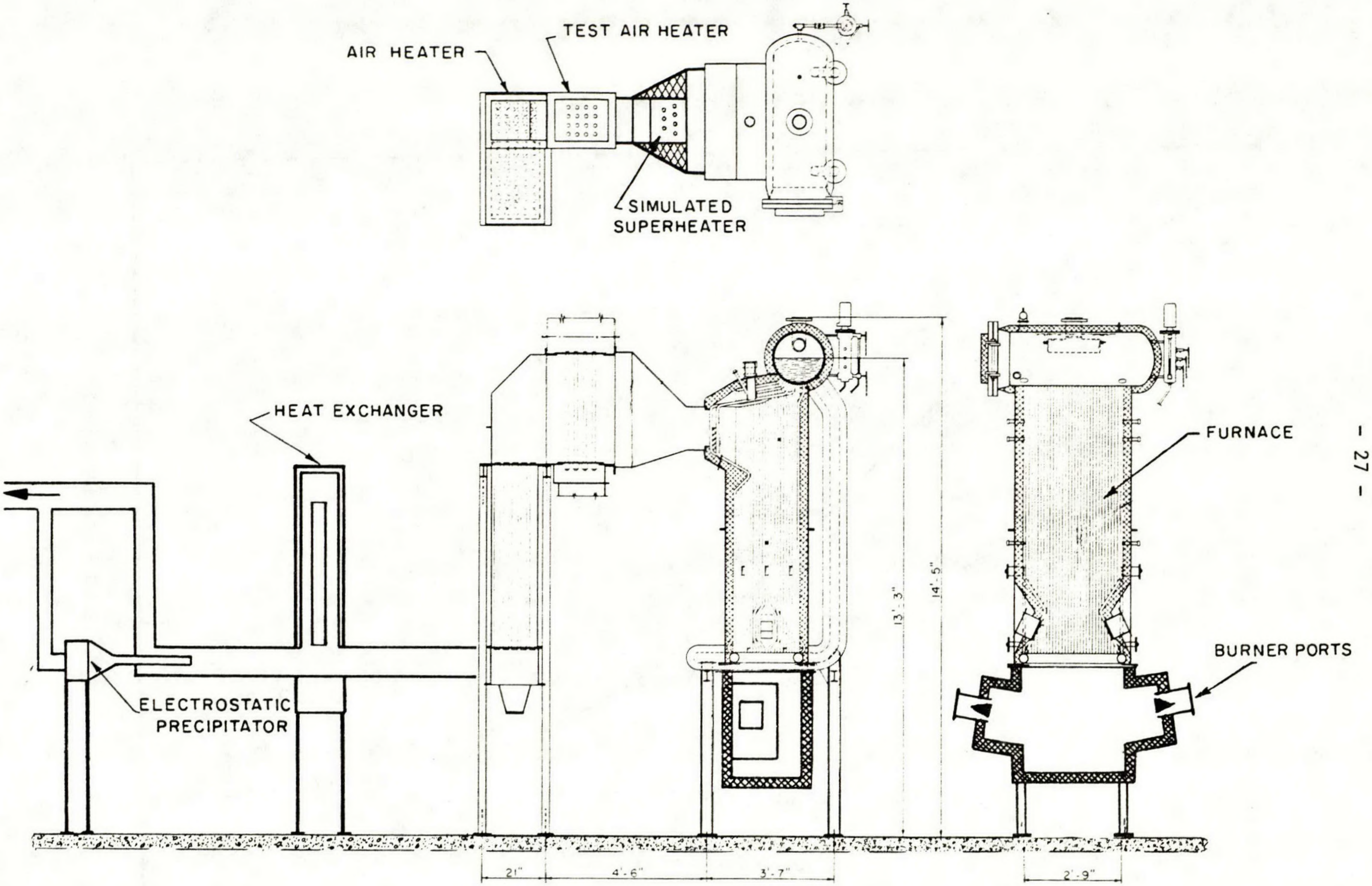

FIGURE 1. The Pilot-scale Research Boiler.

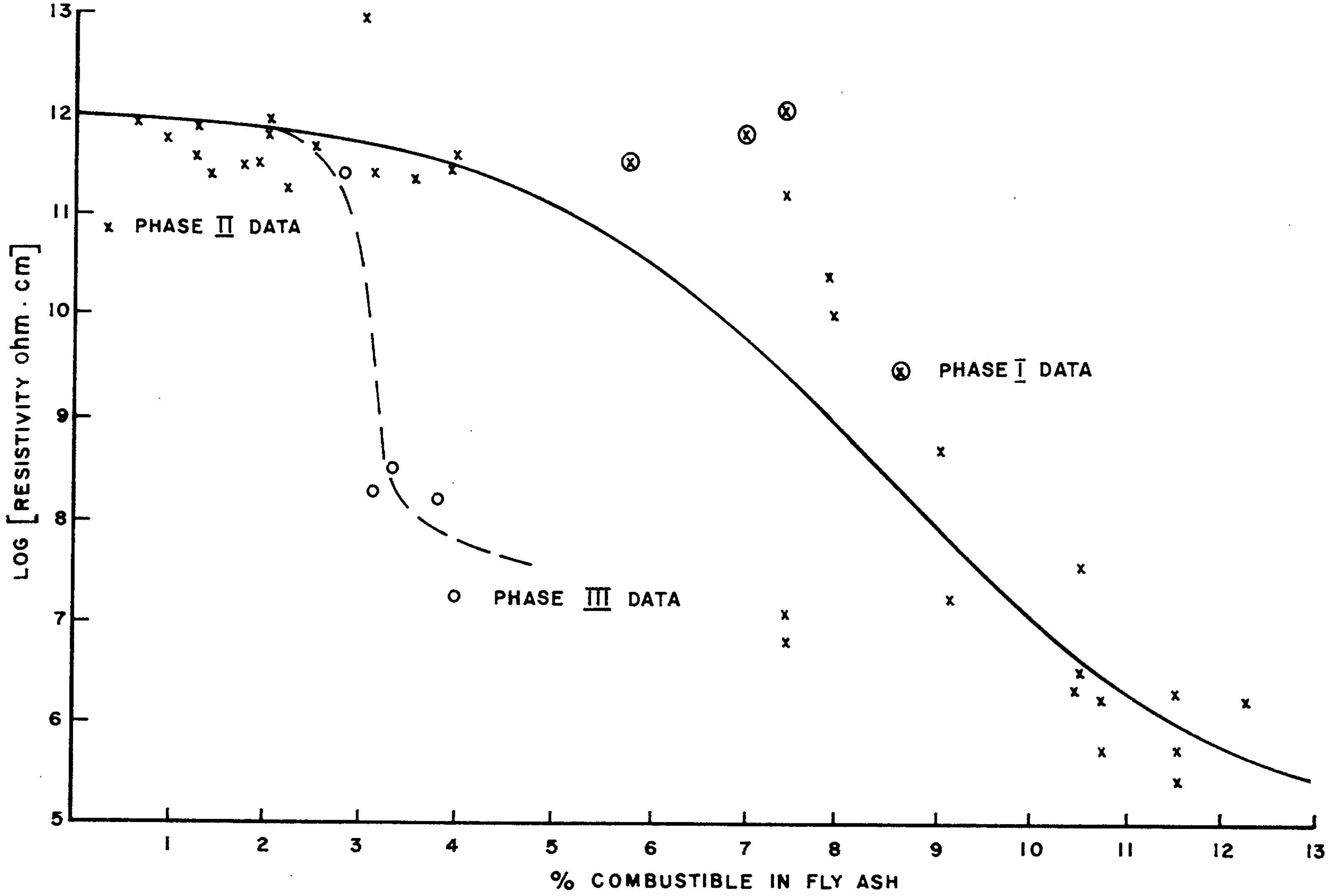

FIGURE 2. The Effect of Carbon Content on Fly-ash Resistivity.
(all data)

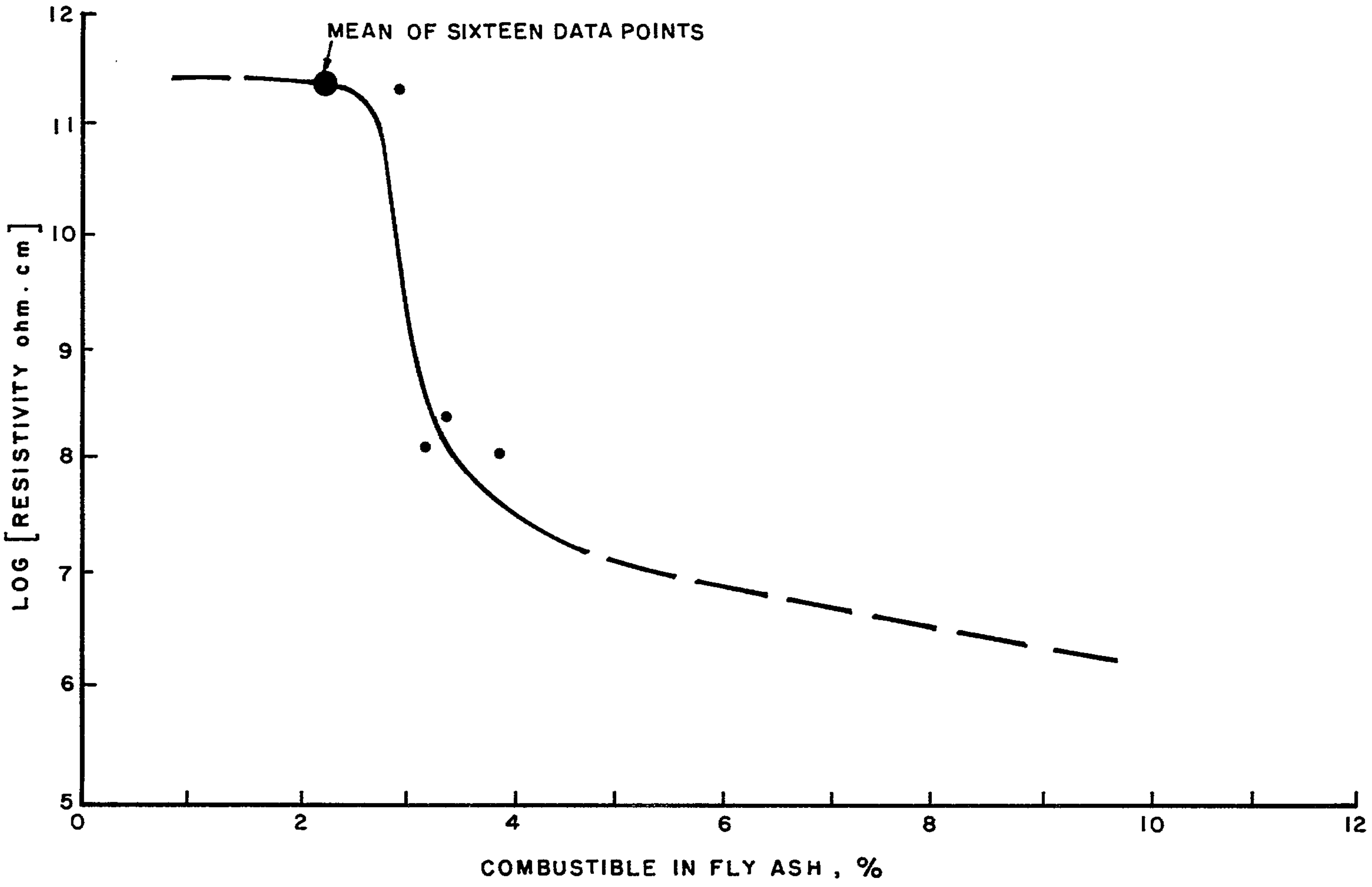

FIGURE 3. The Effect of Carbon on Fly-ash Resistivity.
(Phase III data only)

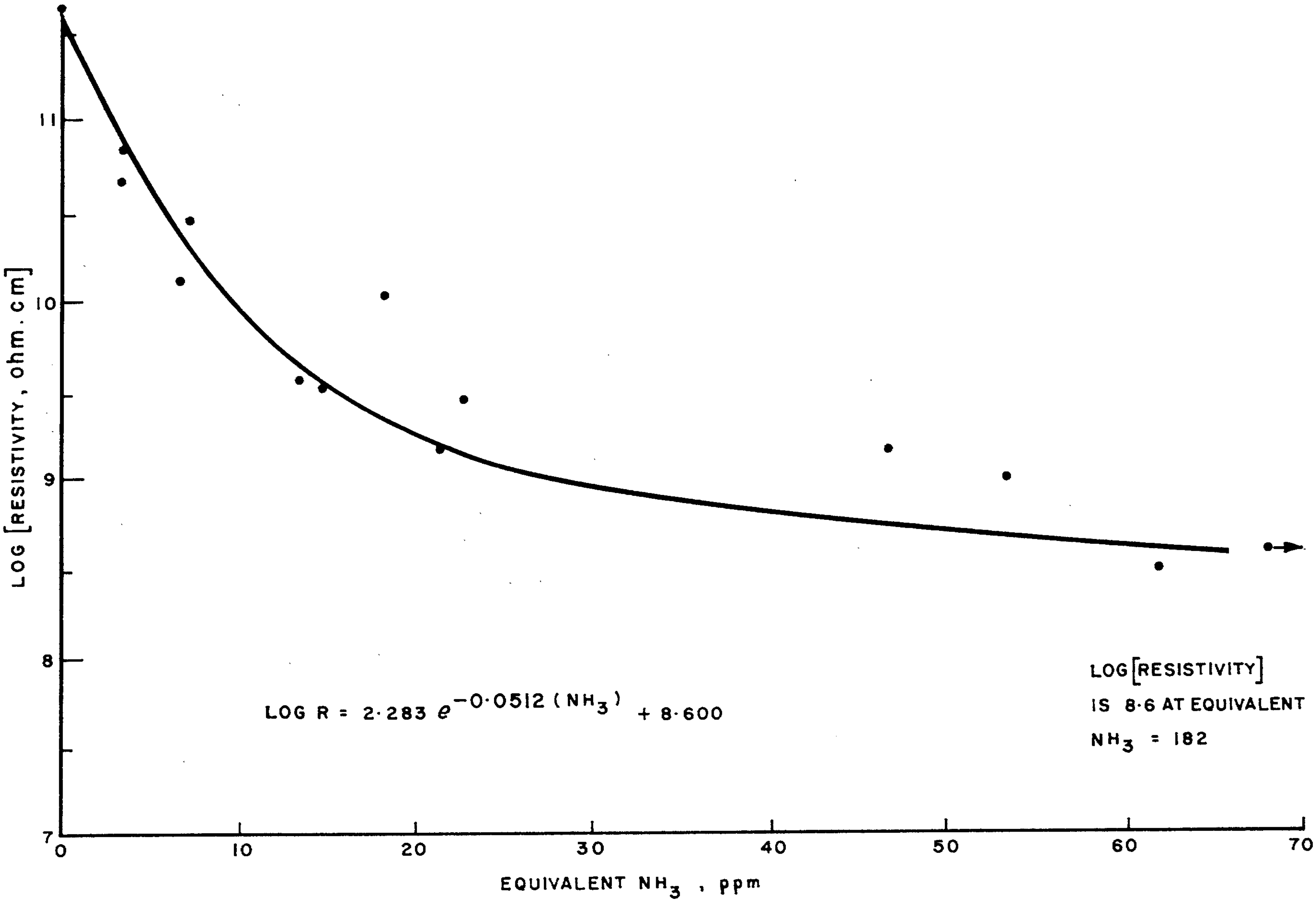

FIGURE 4. The Effect of Ammonium Sulphate Addition on Fly-ash Resistivity.

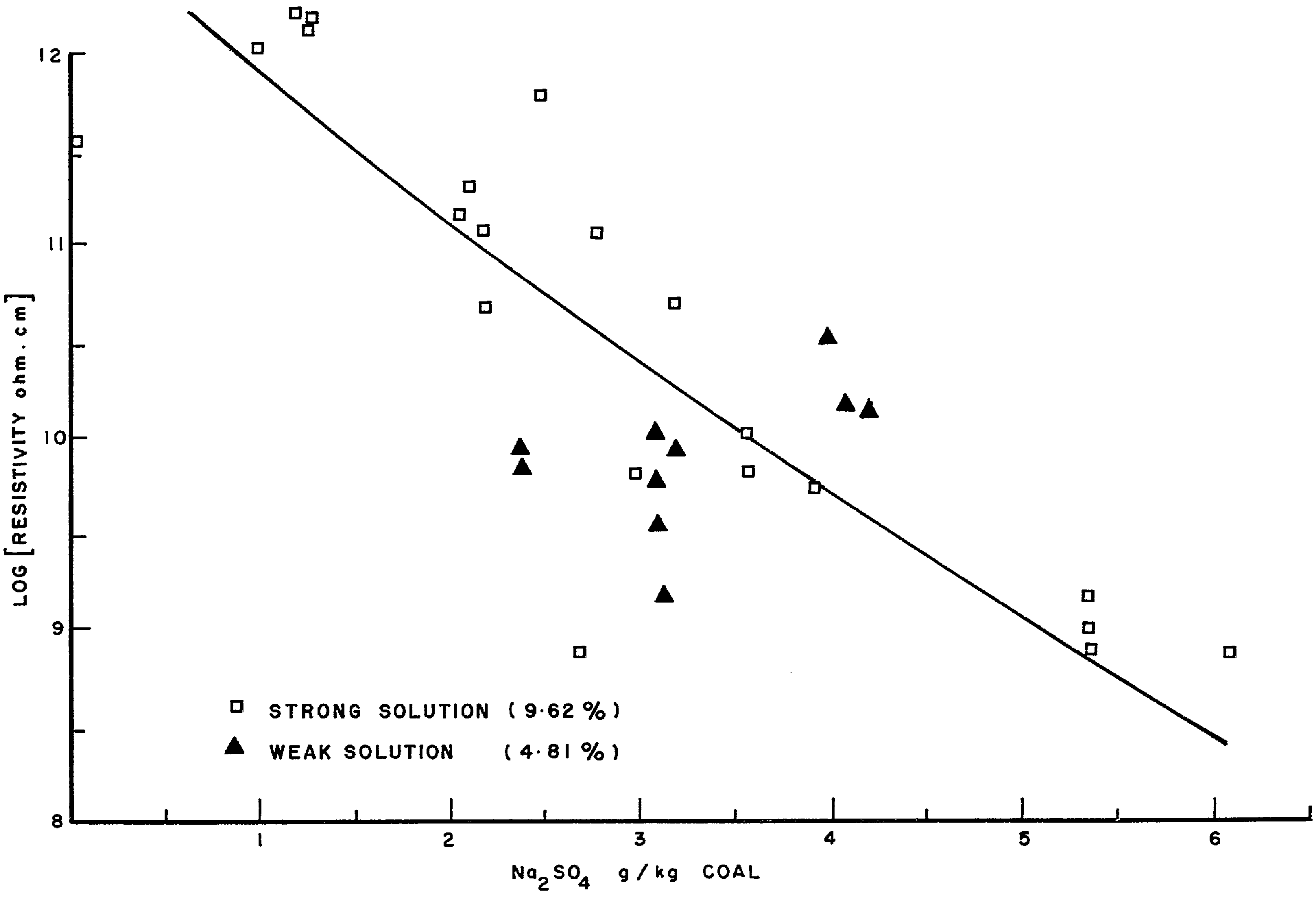

FIGURE 5. The Effect of Sodium Sulphate Addition on Fly-ash Resistivity.

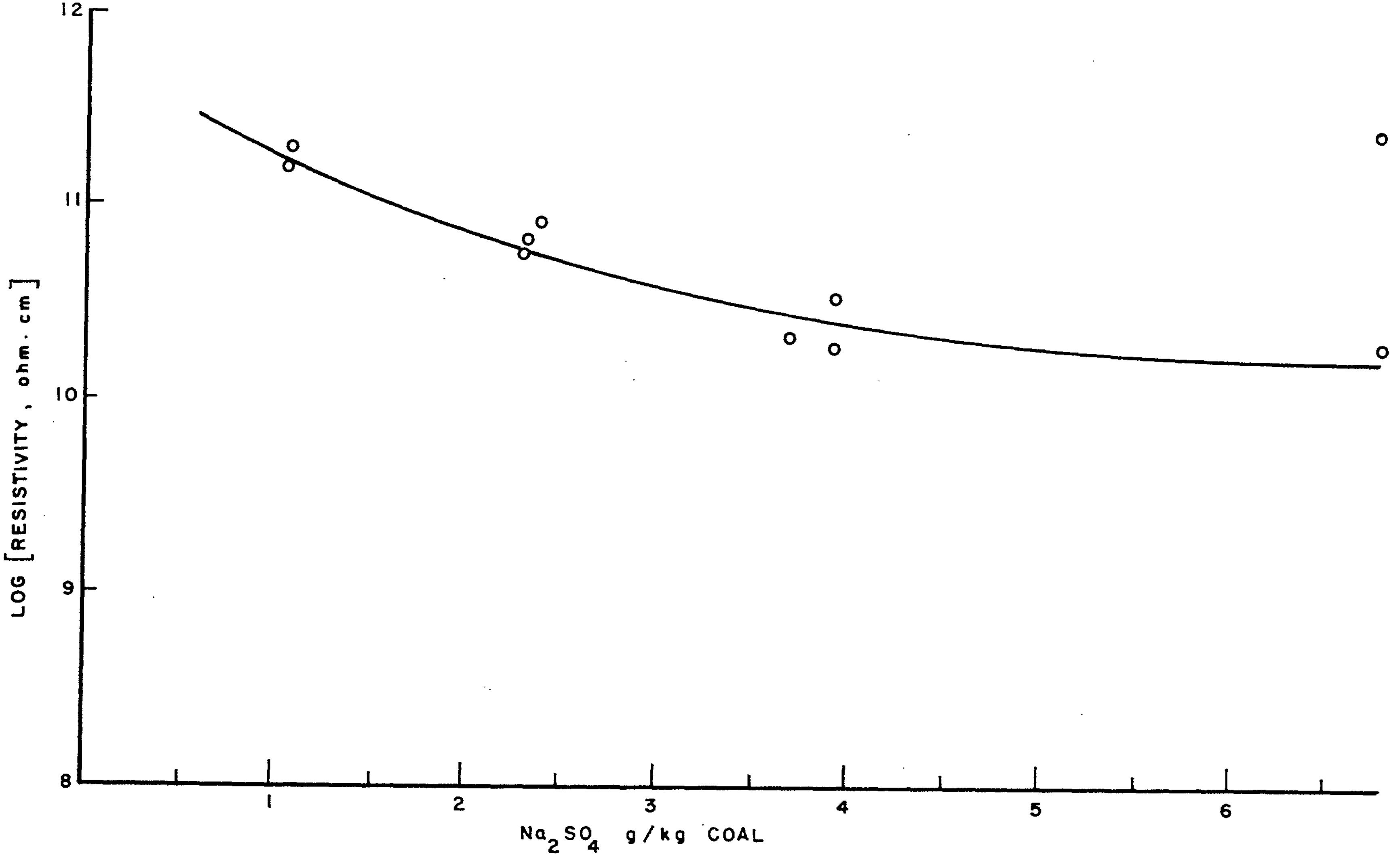

FIGURE 6. The Effect of Sodium Sulphate Addition on Fly-ash Resistivity. (addition to the coal feed)

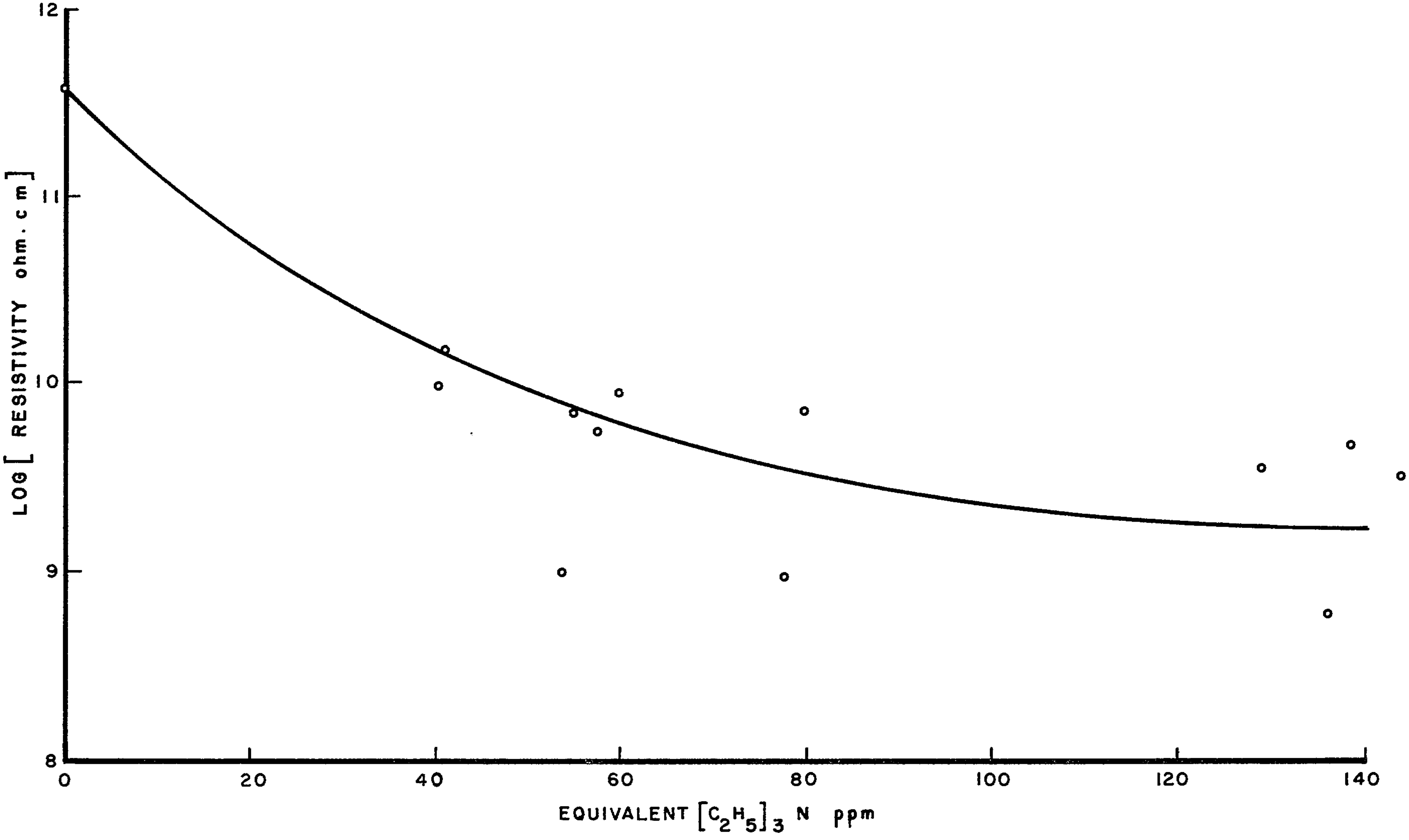

FIGURE 7. The Effect of Triethylamine Addition on Fly-ash Resistivity.

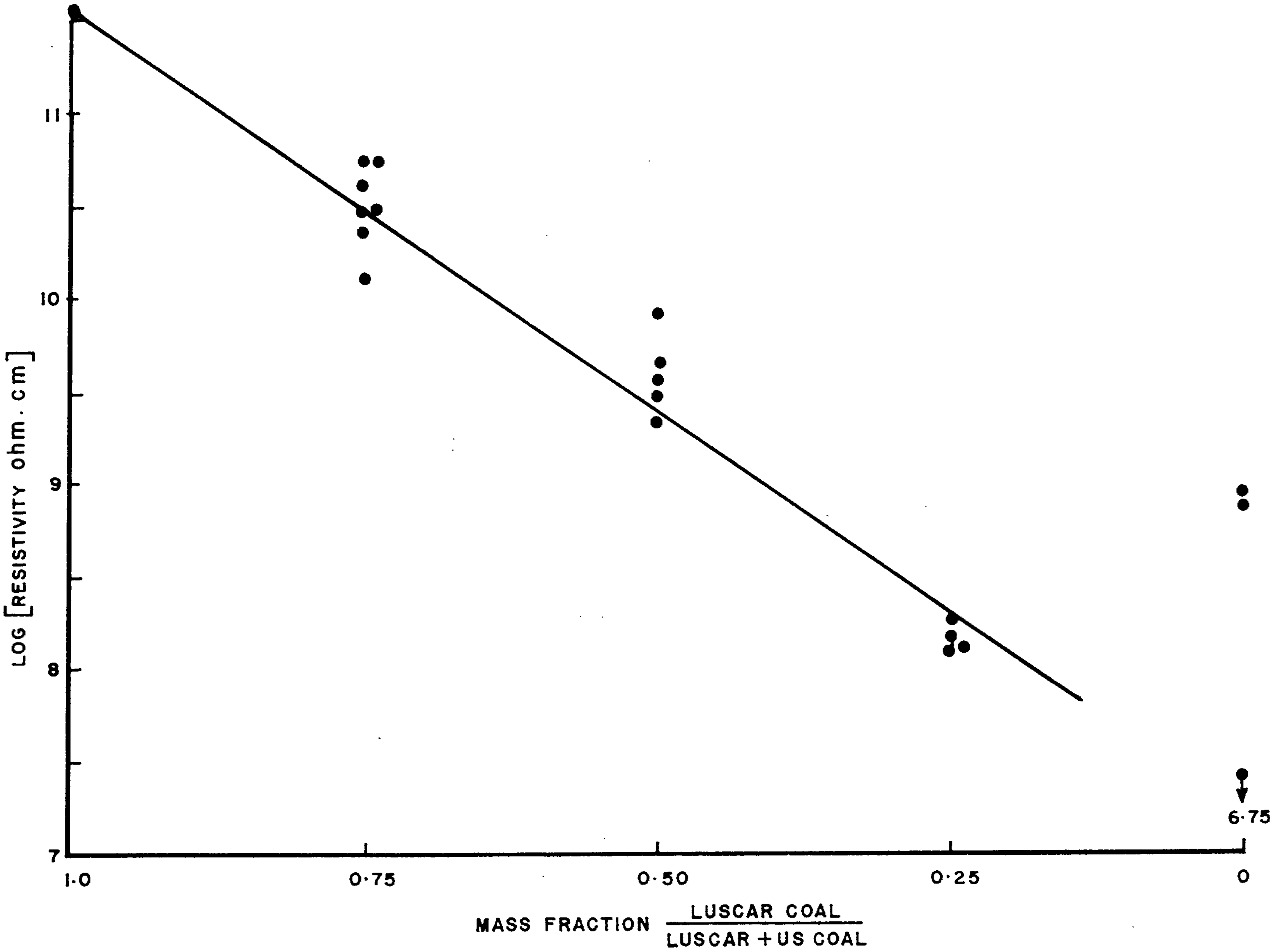

FIGURE 8. The Effect of Coal Blend Rates on Fly-ash Resistivity.

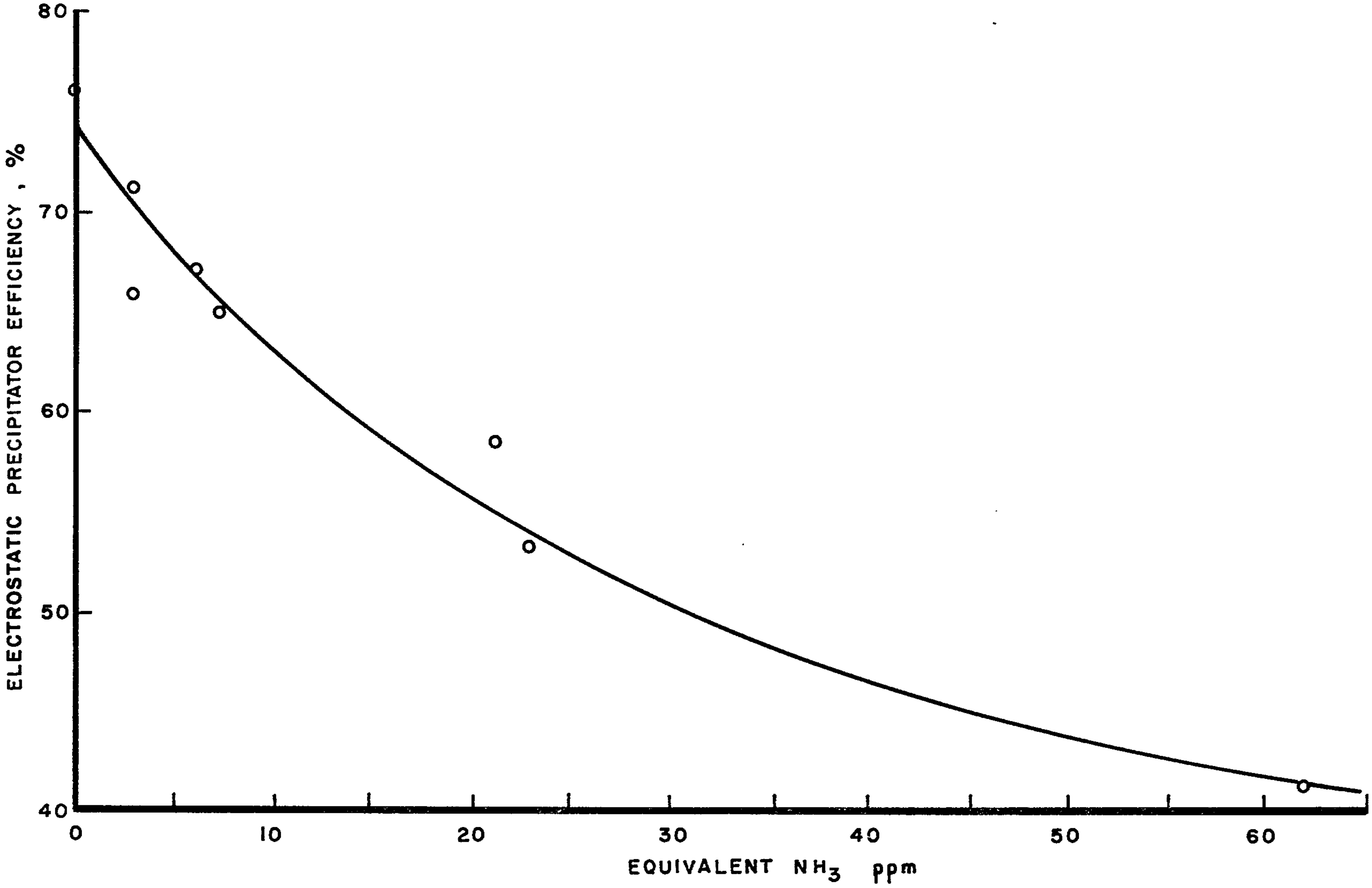

FIGURE 9. The Effect of Ammonium Sulphate on Electrostatic Precipitator Efficiency.

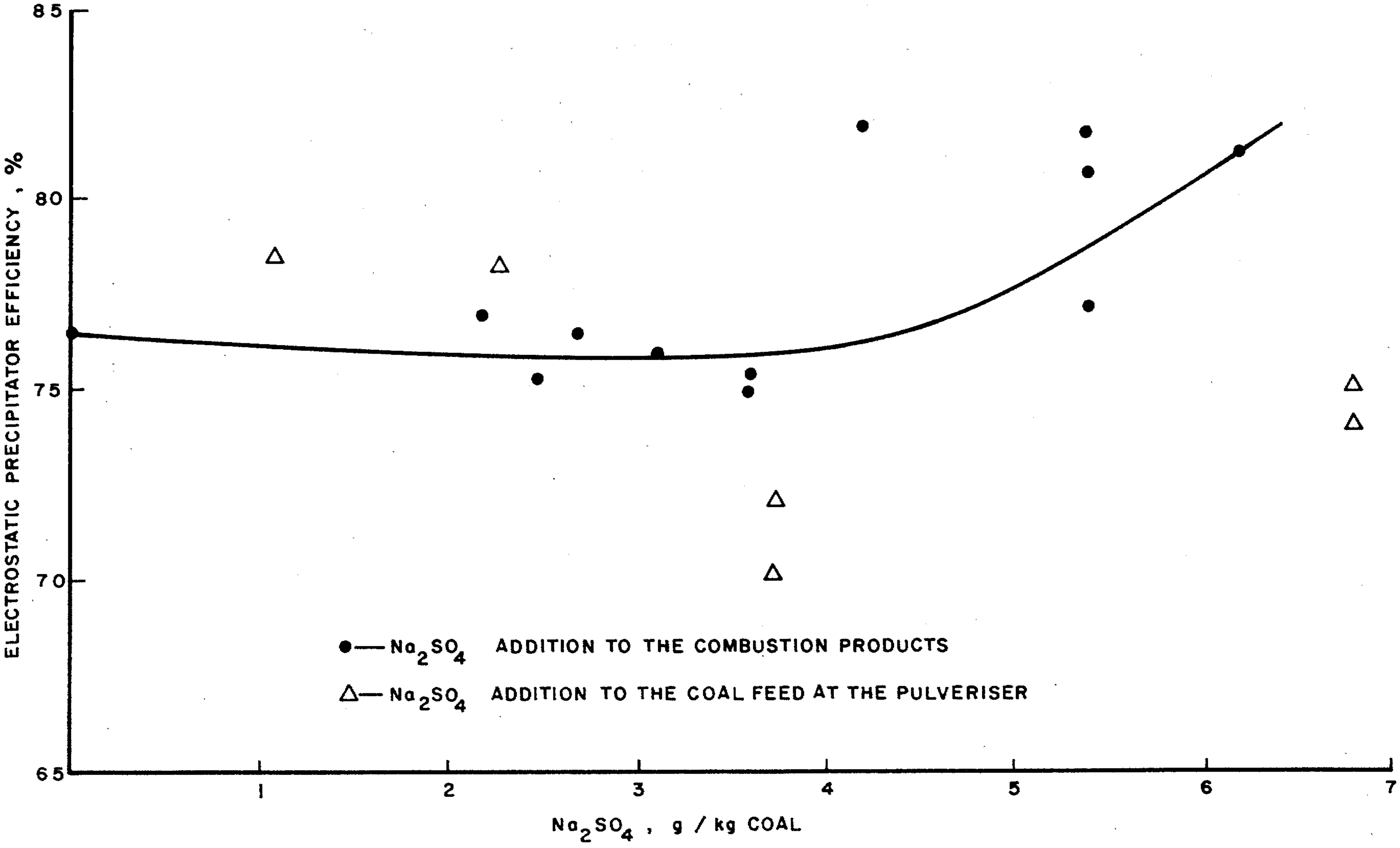

FIGURE 10. The Effect of Sodium Sulphate on Electrostatic Precipitator Efficiency.

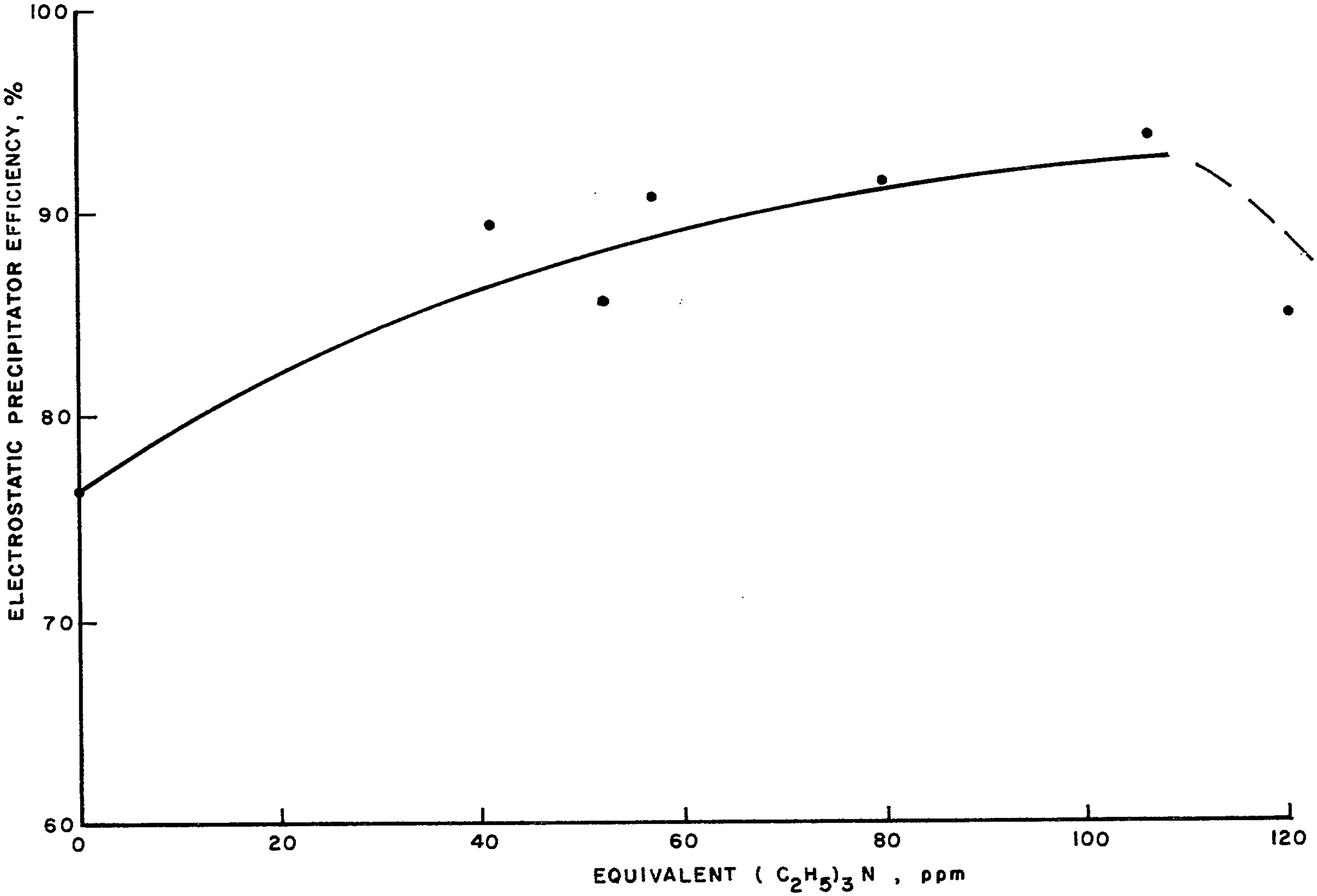

FIGURE 11. The Effect of Triethylamine on Electrostatic Precipitator Efficiency.

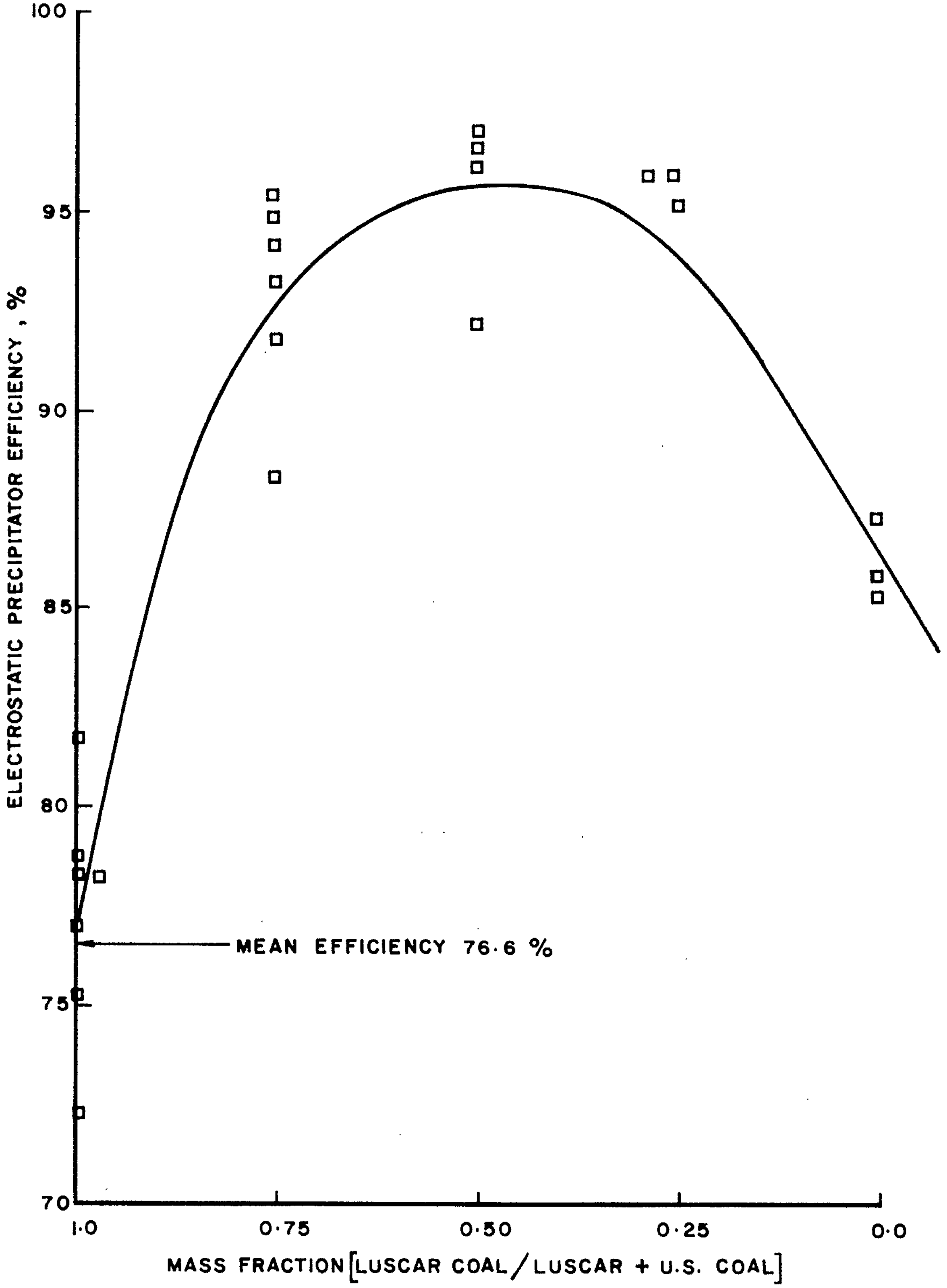

FIGURE 12. The Effect of Coal Blend Ratio on Electrostatic Precipitator Efficiency.

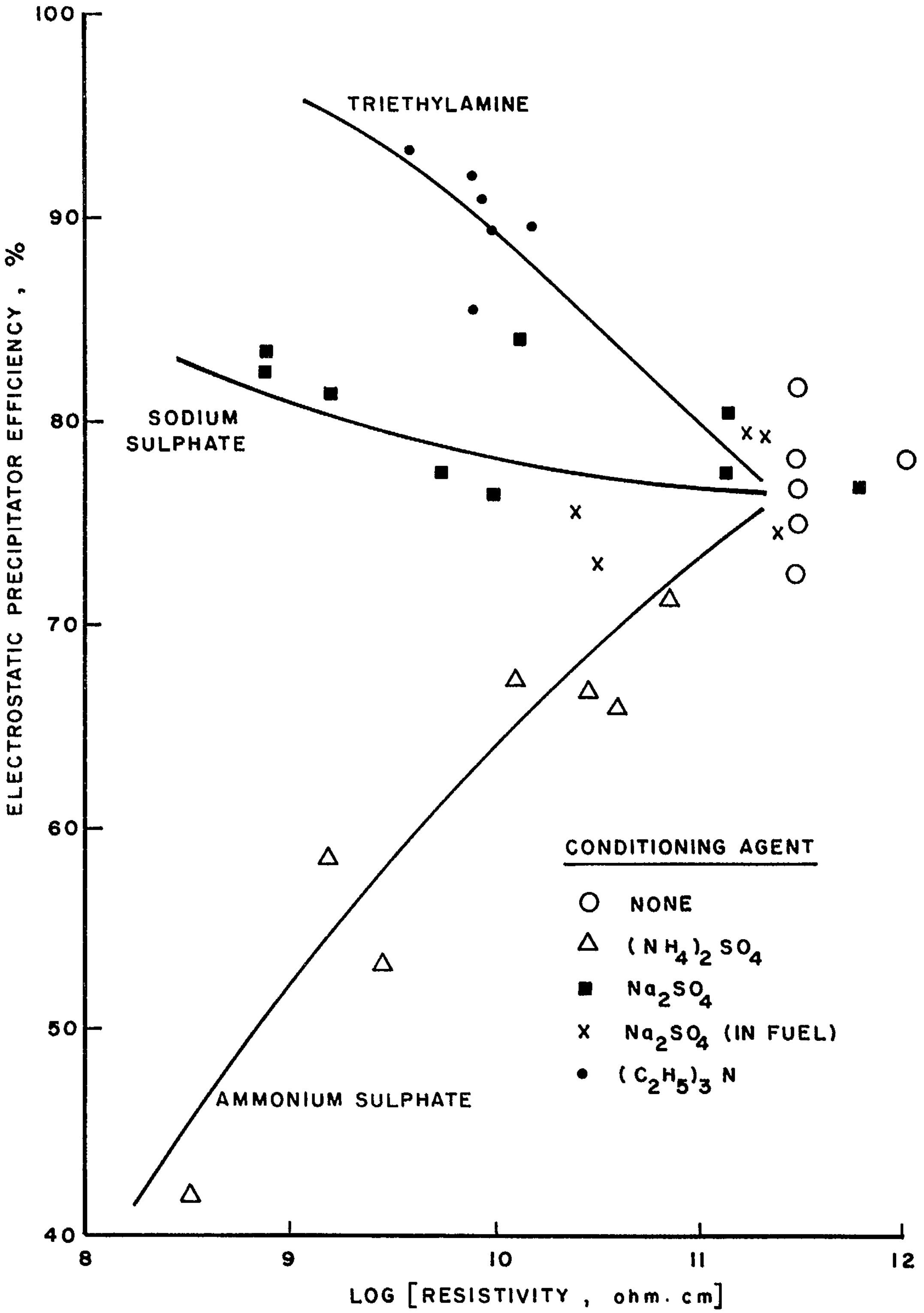

FIGURE 13. The Relationship Between Fly-ash Resistivity and Electrostatic Precipitator Efficiency.

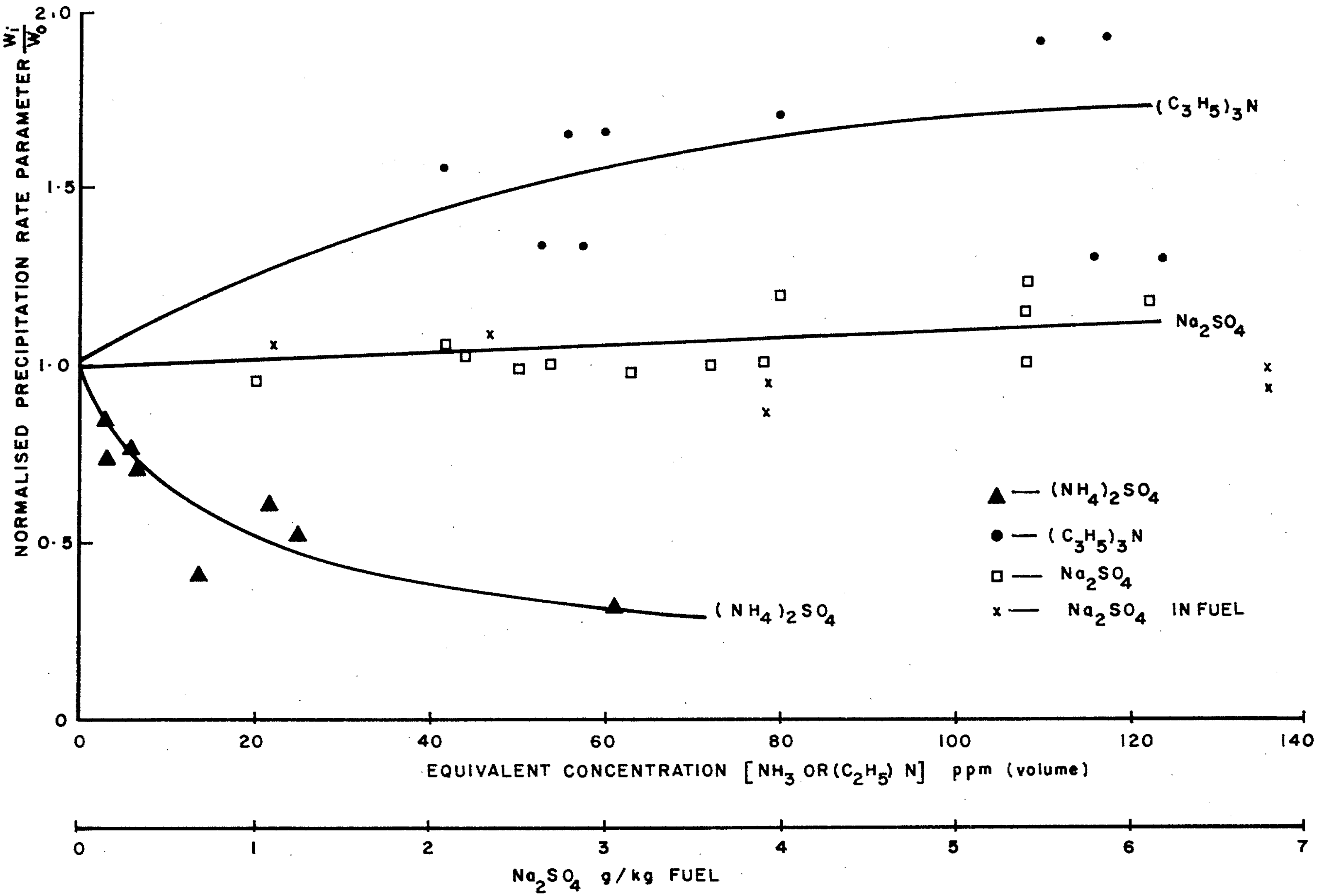

FIGURE 14. The Effect of Conditioning Agents Used in Phase III of the Precipitation Rate Parameter.

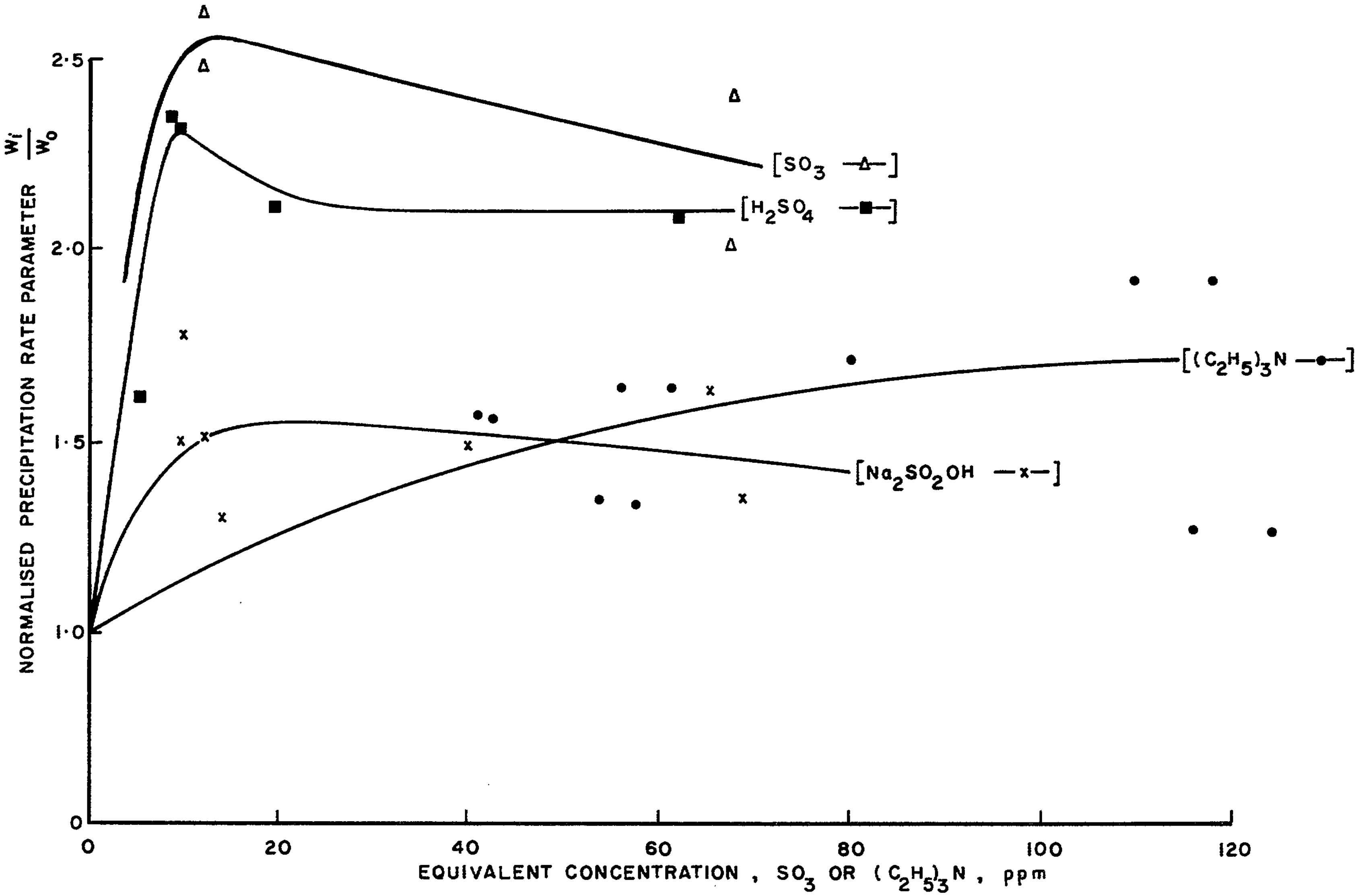

FIGURE 15. The Effect of Selected Conditioning Agents on the Precipitation Rate Parameter.

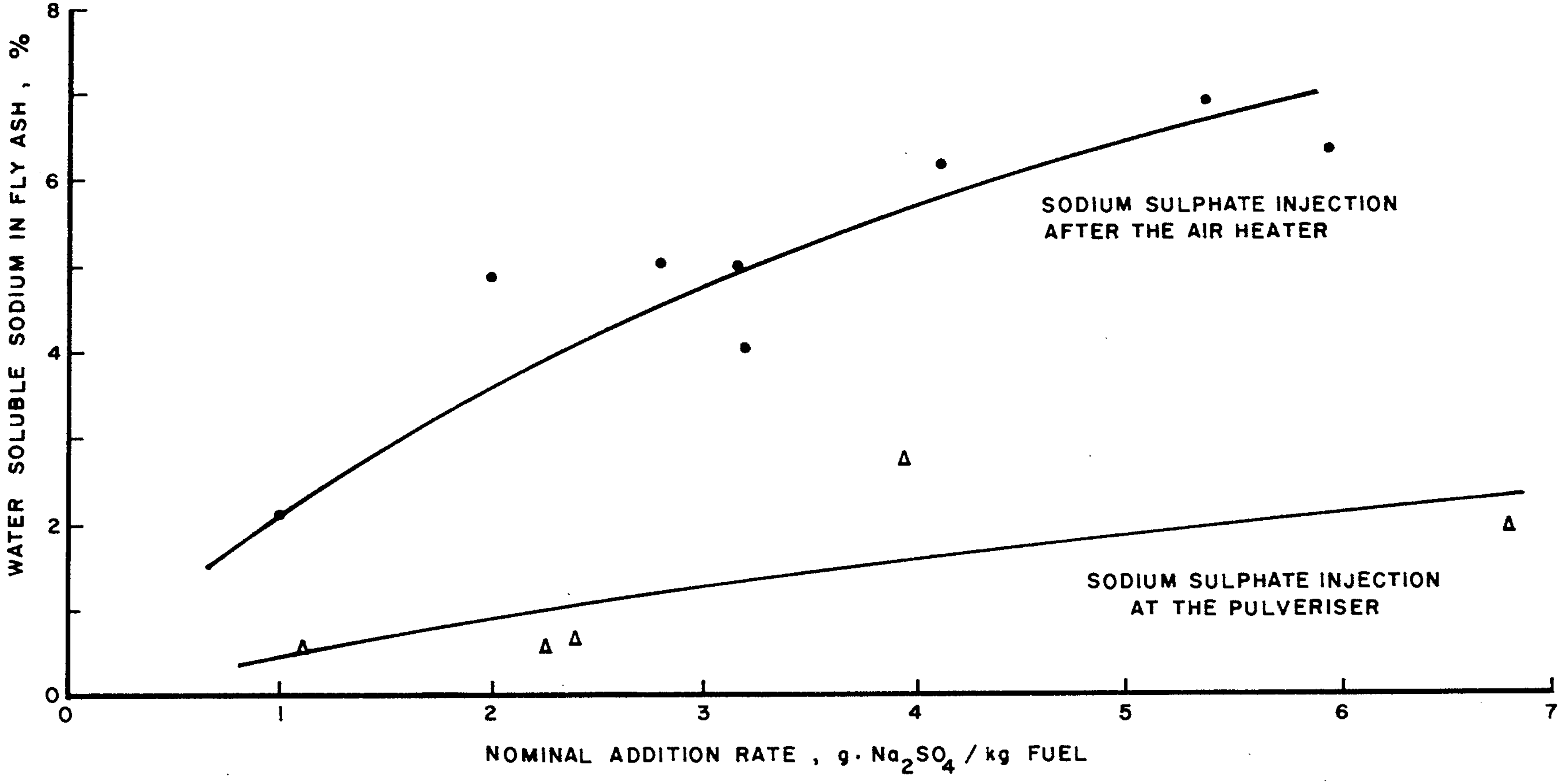

FIGURE 16. The Effect of Sodium Sulphate Addition on Water Soluble Sodium Content of the Fly-ash at the Precipitator Inlet.

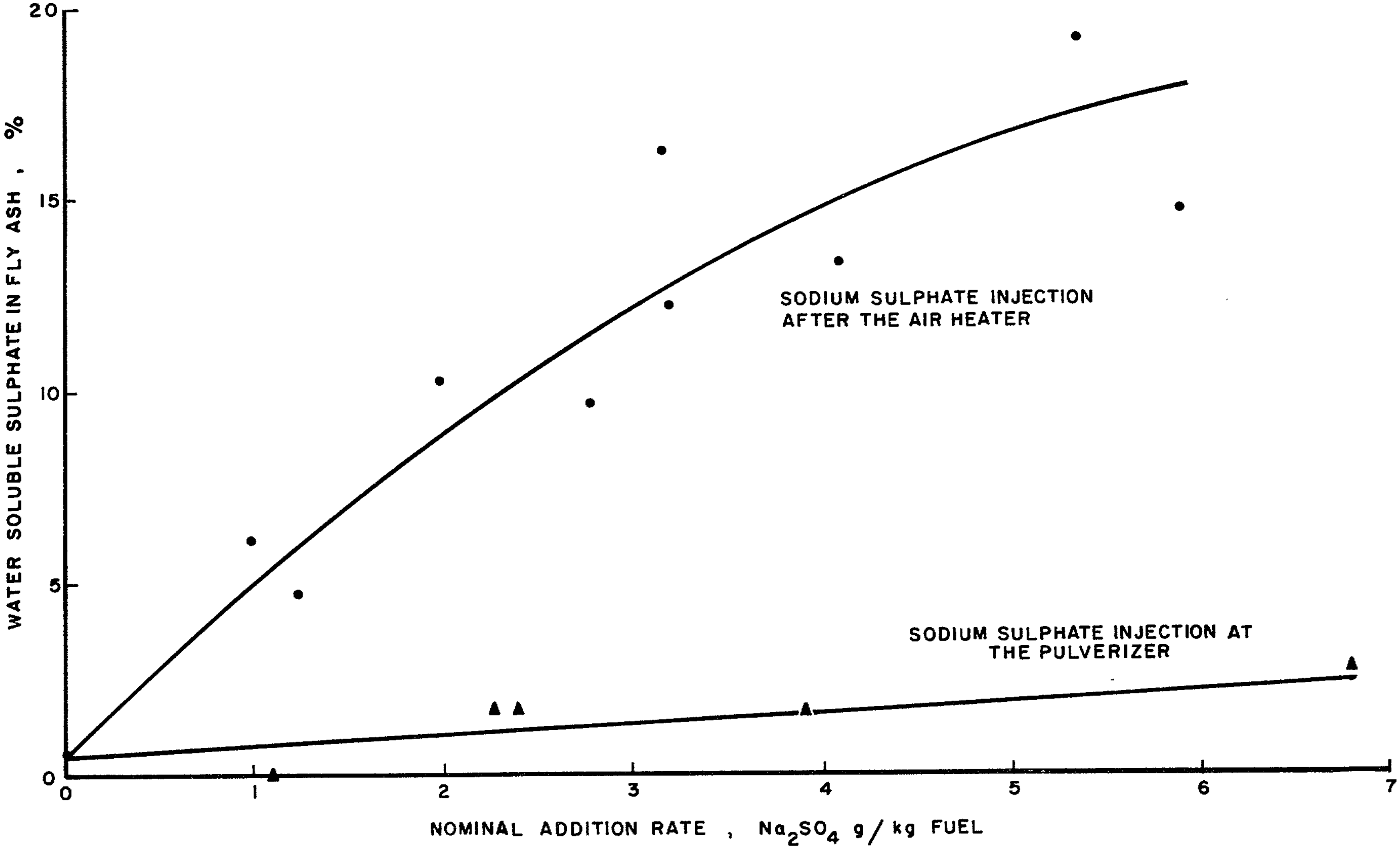

FIGURE 17. The Effect of Sodium Sulphate Injection on the Water Soluble Sulphate Content of the Fly-ash.

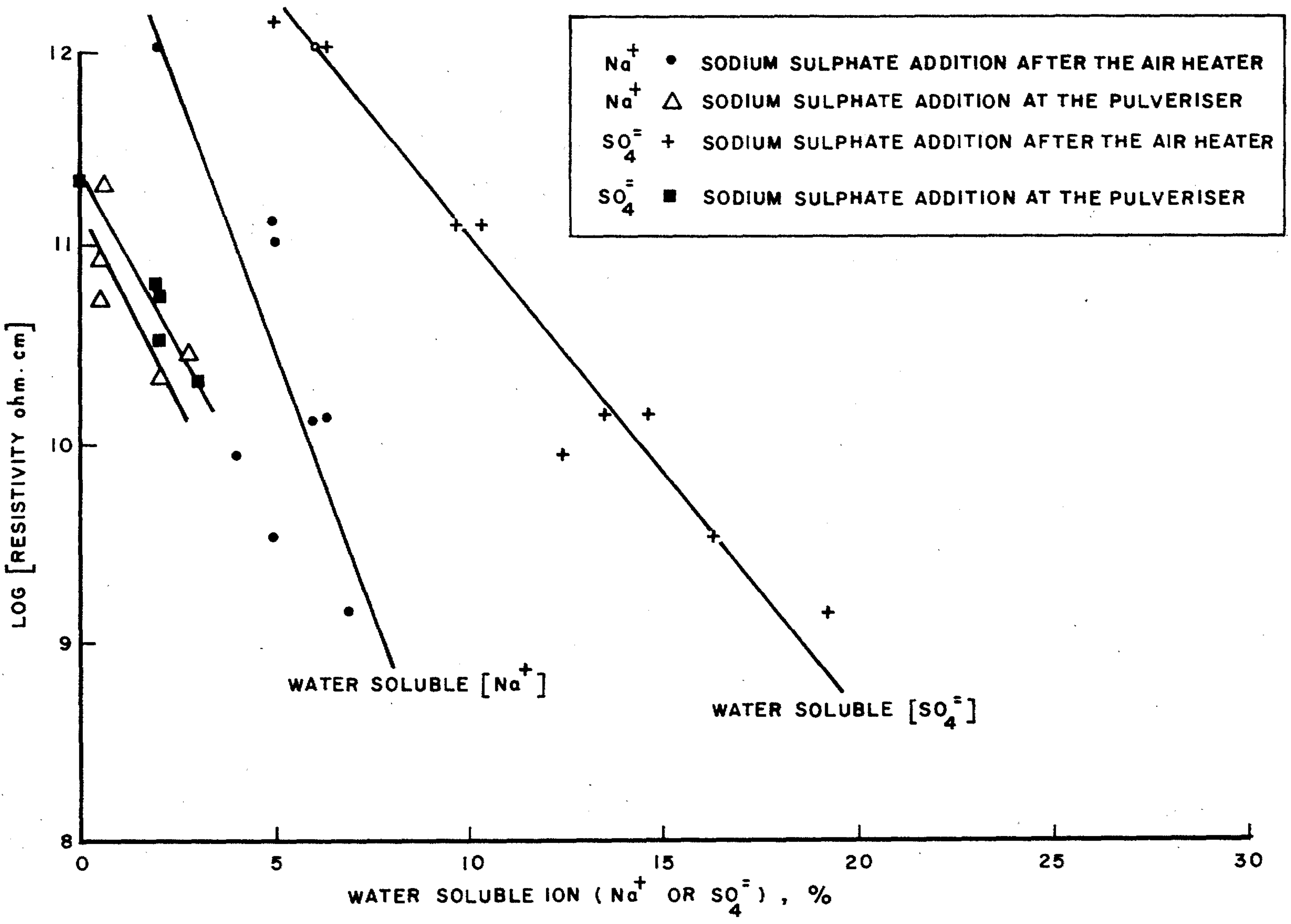

FIGURE 18. Fly-ash Resistivity as a Function of Water Soluble Na and SO4 in the Fly-ash.