Improvement of Fine Particles Collection Efficiency in Large Pulverized Coal Power Plants. ESPs Retrofitting to Hybrid Collectors

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1. Abstract

The last European directive (2001/80/EEC) for Large Combustion Plants limits the emission of particulate matter in E.U. to 50 mg/Nm^3 for ≥ 500 MWth existing coal power plants and to 30 mg/Nm^3 for ≥ 100 MWth new facilities. In other hand, it is probable that next European regulations will limit the fractions more difficult to collect: PM10 and PM2.5. These limits can be difficult to reach considering only existing ESPs, particularly for some high resistivity ashes.

In this sense, this paper describes a series of pilot plant tests carried out in order to enhance the ESP efficiency and to prove the new emergent hybrid collector (HyColl) technology applied to flue gases from coal power plants. The ESP tests have been performed with the main objective of studying ESP behaviour when different coals and different filter configurations/energisation methods are used. The primary aim of this study was to reach conclusions about the ESP design and sizing optimisation for high efficiency applications. In the other hand, the HyColl tests have been performed with the objective of comparing the efficiency and costs of this new technology with ESP technology.

A HyColl consists of an ESP followed by a fabric filter (FF) installed in the same casing. The tests have been carried out in an ESP/HyColl pilot plant developed within the HyColl Project (ECSC 7220-PR/079). The pilot plant consists of an ESP with three electric fields followed by a 32 bags FF section, processing 15,000 Nm^3 of real flue gases extracted from the flue gas ducts of a power station. The pilot plant is located at Los Barrios P.S. (Spain), but additional evaluation tests have been performed at Dürnhror P.S. (Austria).

Modifications on design and operation parameters of ESP and HyColl have been tested according to the factorial design of experiments in order to obtain their optimisation for collecting particulate matter in coal combustion flow gases.

KEYWORDS: Electrostatic precipitator, hybrid collector, efficiency, retrofitting, emission reduction

2. Introduction

Although coal ESP technology is consolidated worldwide and a large amount of research and practical experience exists, more efforts are still needed to improve filter performance in order to accomplish the new PM emission legislation in Europe, mainly when high-resistivity ashes are involved. In these cases the units find serious difficulties to achieve the required efficiency and operation stability, and an important ESP oversizing is often used to reach the very high efficiency presently demanded to particulate control units.

In the 90's some new concepts have been introduced by ESP manufacturers trying to achieve the double objective of increasing ESP efficiency and, at the same time, reducing both capital and operating costs. Among these new concepts, the most interesting issues are the following: wide plate spacing [1], new rigid electrodes [2, 3], intermittent energisation [4, 5], and new electrical control systems [6] in addition to flue gas conditioning. Therefore, new units tend to have very different geometry, electrode design, and power supply than older ones. In addition, some insight has been made on rapping improvement and on advanced control systems. As a result, a better performance of ESPs is now expected, but some lack of knowledge remains, at least among ESP users, about the quantifiable real benefits of these changes and about their applicability to fine (PM10, PM2,5) and high resistivity particles. In fact, the new ESP concepts have not always resulted in parametric optimisation of the other related ESP components, and they have been often promoted taking into account their cost advantages more than the actual improvement on ESP performance.

The HyColl concept appears in the late 90's as a useful tool for efficiency improvement and saving costs in the PM collection compared with only ESPs [7]. The synergism between the dust load reduction and pre-charge produced in the ESP fields and the use of a high-tech micro-pore filtering media in the bag filter drives to a very high efficiency using air-to-cloth ratios higher than those used in modern pulse-filters. Therefore, a wide application field would be open: the retrofit of existing coal ESPs to be converted into HyColls by substitution of their last fields for bag houses installed in the same casing.

3. Experimental methodology

Experimental Facility

A pilot plant has been designed and built to accomplish the test requirements [8]. The pilot plant is located at Los Barrios P.S. (Cádiz, Spain). This coal-fired power station consumes various types of international bituminous coals. The pilot installation is connected to a flue gas duct upstream of the power plant ESP and it includes a pilot ESP (PESP) followed by a FF and its auxiliary units and control systems. Figure 1 presents the plant layout in Los Barrios P.S., where it should be noted that the plant also includes a by-passed spray drier desulphurisation reactor and a fluidised bed desulphurisation plant (LFC).

The PESP main characteristics are presented in Table 1. The PESP design includes the following special features:

- All PESP internals (plate curtains, electrode frames, rapping hammers, etc.) are movable and it is possible to modify plate spacing, number of gas passages, electrode type, and electrode number fast and directly from the inside of the filter.
- The PESP energisation system is capable of generating rectified continuous current or intermittent (pulsing) current, and even of combining both according to the electrical operating conditions of the filter.
- The pilot installation has a system of two fans: a forced-air fan and an induced-draft fan, which allows simultaneous regulation of gas flow and PESP operating pressure. This system was conceived to permit the operation of the PESP at neutral pressure (atmospheric pressure), avoiding the possibility of parasitic entries of air to the precipitation chamber.

The FF type selected was a pulse jet fabric filter. This type of filter allows a more effective and controlled dust cleaning. The FF main characteristics are:

- Bags of full industrial size were selected in order to simulate full-scale behaviour. However a lightly longer (6 m) than the habitual bag longitude was selected to evaluate the effectiveness of cleaning.
- Various types of novel filtering media were analysed to be installed in the FF. Finally, a micropore filtering media composed of Ryton felt with a PTFE membrane was selected as the more adequate for the ash and gas characteristics.
- According to the gas flow and the foreseen filtration velocities in the tests, a total number of 32 bags were installed. It was also decided to permit the possibility of changing the operative bag number, mounting groups of isolated bags in order to modify the filtration velocity. As a result, the FF is capable of operating with 16, 24 or 32 active bags.
- In relation to the active groups of bags, the active filtration area can be selected as 45, 68 or 90 m2.
- The flue gas flow treated in the FF can vary within the interval of 9,000 - 18,000 m3/h.
- Air-to-cloth ratios varying from 5 to 10 ft/min were proved.
- A wide and versatile cleaning control system was installed in order to study the best cleaning

conditions in FF. The programmable cleaning periods and blowing pressure level allowed by the system cover the range from low to high-energy pulses.

The pilot plant was equipped with an automatic control system. The control system acts over the most important operating variables (flow, pressures, and temperatures), and with an automatic data-acquisition system that continuously registers and stores the state of the units, meter data, and electrical conditions of the PESP. Thus, the variables of the tests carried out can be programmed automatically and the results can be easily and exhaustively processed.

Methodology of ESP tests

The PESP behaviour was studied based on experimental tests programmed to find its sensitivity to various parameters. The testing program was designed with matrices of parametric tests obtained by applying factorial analysis of experiments.

The tests sought to establish the PESP efficiency under the different conditions reflected in the matrix of tests for each type of coal. Within the limitations imposed by working in series at an industrial plant, the operation variables were maintained as stable as possible, carrying out the tests during steady state boiler operation in the absence of interferences. Likewise, tests were made at full load conditions to maintain the parameters of the gases to be processed within narrow limits.

Due to the objective of these tests, accurate particle concentration values were required to find the unit efficiency under different testing conditions. In all tests, the concentrations were evaluated by isokinetic sampling of particles using two units operating simultaneously at the precipitators inlet and outlet. Samplings were carried out according to EPA method no. 17 [9].

Selected parameters for tests plan and its levels are shown in the test matrix (Table 2) [8].

The properties of both coals are shown in Table 3. It can be seen that coal A is characterised by a medium ash content and a very high ash resistivity; whereas coal B shows a lower ash content and lower resistivity. Although both coals have similar sulphur content and produced ASTM class F ashes, substantial differences in fly ash resistivity should be related with the observed differences in coal ash composition.

Other variables affecting precipitation, as rapping frequency, temperature, and energisation control, were kept constant during tests to simplify the experiments and results processing.

Methodology of HyColl tests

HyColl tests were carried out in order to know the improvements in efficiency and to determine the optimum design and operational parameters of fabric filter. Special attention was paid in the tests to the assessment of PM10, PM2,5 and metal emissions. The selected measuring methods for pilot plant testing were:

- Total particulate matter: EPA Method 17 (HyColl inlet and outlet)
- PM10, PM2.5: Set of cyclones at inlet and cascade impactor at outlet.
- Trace metals: EPA Method 29 (HyColl inlet and outlet). [10]

The adopted test methodology for pilot plan testing was based in the following approach:

- A parametric sensitivity analysis using a reduced number of tests (test matrix).
- Target variables: Collection efficiency, interval between cleaning cycles, bags life.
- Manipulated variables: Filtration velocity (air-to-cloth ratio), ESP efficiency (number of active ESP fields), filter pressure drop, bag cleaning parameters and cleaning mode.

Two operational cleaning modes were tested:

- Discontinuous cleaning, simulating the isolation of a compartment of the bag filter during the cleaning

- Continuous cleaning, maintaining the gas flow during cleaning periods

The test matrix for the HyColl testing stage was established as indicated in Table 4.

4. Test results

4.1 Results of ESP tests

Electrode selection

To experimentally assess the electrode selection for different applications and filter configurations, three electrode types have been tested. Figure 2 presents the voltage-current intensity characteristics for the different electrodes. The reference V-I curves obtained under air load at ambient temperature and clean plates are presented in this figure together with curves obtained under operating conditions with high resistivity ash, as representative of the extreme conditions inside the filter (V-I curves with low resistivity ash are close to reference curves). It can be seen in Figure 2 that the characteristics of used electrodes cover the performance range of commercial geometries, and they can be classified as follows:

- The barb wire is a high energy electrode, low-voltage/high-current producer.

- The pipe-and-spike electrode is a medium energy electrode producing moderate-voltage/moderate-current.

- And the twisted rod electrode is a low energy electrode with typical high-voltage/low current characteristics.

Figure 2 also indicates the effect of plate spacing on the electrical behaviour of electrodes. A wider plate spacing always produces the expected increased voltage coupled with a reduced current. Although in some cases, i.e. using the pipe-and-spike electrodes, the transition from a 400 to 500 mm plate spacing does not produce a substantial modification of V-I curve.

A remarkable advantage of the use of a wider plate spacing when high resistivity ash is collected lies in the improvement of electrode performance due to suppression or reduction of undesirable phenomena, like back-corona. This is clearly observed in the V-I curves of Figure 2 corresponding to filter operation conditions (dirty plates). Under these conditions of high resistivity, some of the V-I curves show the vertical rise in current typically associated to the establishment of back-corona. Back-corona production is reduced by an increase on plate spacing or by using a lower energy electrode. In accordance with V-I curves, severe back-corona was produced by barb electrodes in a 300 mm configuration, and some evidence of back-corona remains at 400 mm with these wires and at 300 mm with pipe-and-spike electrodes.

Collection efficiency

The effect of both design parameters - plate spacing and electrode type - on PESP collection efficiency is presented in Figure 3. In this figure, penetration trends obtained with high and low resistivity fly ash and with each tested PESP configurations using continuous energisation are plotted. Two types of data have been considered:

1. Measured penetration for all tested configurations using the same gas velocity (baseline value of 1.1 m/s). This approach implies a variation in the PESP specific collection area (SCA) when plate spacing is modified. Data are representative of the performance of precipitators with the same approximate volume having different plate spacing. Corresponding SCA values are:

   - 300 mm .- 37.8 $m^2/(m^3/s)$
   - 400 mm .- 28.2 $m^2/(m^3/s)$
   - 500 mm .- 22.6 $m^2/(m^3/s)$

2. Estimated penetration for a constant SCA value in each configuration. A SCA of 30 $m^2/(m^3/s)$, intermediate between the experimental values, has been selected. In this case, data are representative of precipitators with the same collecting area despite their different plate spacing. Represented figures have been calculated from correlation of experimental values.

From observation of Figure 3, the following information can be extracted:

- The barb electrode, a high-power geometry, produces the best ESP performance when low-resistivity ash is collected and the baseline plate spacing (300 mm) is used; also, as it was expected, it gives worse results than the other electrodes, at baseline conditions, when ash resistivity is high. However, a substantial change in performance is produced when plate spacing is increased. A strong decrease in ESP efficiency for low-resistivity ash is observed when a plate spacing of 400 mm is tested, probably as a direct consequence of associated SCA reduction, whereas a considerable improvement is obtained for high-resistivity ash, despite the aforesaid lower SCA. In this last case, if SCA was maintained a greater improvement in ESP efficiency is predicted.

- The pipe-and-spike electrode gives the best behaviour at baseline conditions for high-resistivity ash and the worst for low-resistivity ash. And also performance trends are opposite when wider plate spacing is used. In this case, the associated reduction in SCA leads to a lower efficiency for a 400 mm ESP processing high-resistivity ash, although predictions indicate a potential efficiency increase for constant SCA. However, it has to be pointed out that a considerable improvement in ESP performance is obtained with low-resistivity fly-ash when increasing spacing from 300 to 400 mm with continuous energisation.

- The twisted rod electrode, a low-power electrode, tends to produce a similar performance than pipe-and-spike electrode for plate spacing of 300 and 400 mm, giving a bit lower efficiency for high-resistivity ash. This electrode also shows a higher potential for performance improvement when modification of plate spacing from 300 to 400 mm is made maintaining SCA.

- Finally, tests using a very wide plate spacing (500 mm), only performed under high-resistivity conditions, always indicate a degradation of ESP performance with respect to the standard wide plate spacing (400 mm), especially for the twisted rod electrode. When a spacing of 500 mm is used a new reduction on SCA appears and needed voltages are closer to TRs maximum design values by which some limitation on electrical performance can be found (as seems to occur for twisted rod electrode). Avoiding the effect of SCA reduction, pipe-and-spike is the only electrode geometry that shows a performance improvement potential, indicating its ability to efficiently support very wide plate spacing designs with proper ESP sizing.

Influence of energisation on ESP Performance

Although new ESP energisation methods, like intermittent wave forms, have been mainly focused to achieve reductions in precipitation power consumption while maintaining performance levels, their effect on efficiency can not be easily predicted without plant testing in real operation conditions. Moreover, the effect of energisation is also coupled with the effect of other factors, like electrode type or plate spacing, which have been conceived mainly to affect ESP efficiency or capital costs, but which also have a considerable effect on power consumption.

The global results of the extensive testing of ESP performance using conventional continuous rectified current and intermittent energisation are presented in Figure 4. This figure contains experimental data for all the tested ESP configurations obtained with the baseline gas velocity and with all ESP fields active.

The most impressive finding is the drastic fall of power consumption with intermittent energisation. Intermittent energisation reduced the average voltage and especially the secondary current, leading to the low power values plotted in Figure 4. In the case of high resistivity, power consumption with intermittent energisation is approximately the same for each plate spacing, independent of the discharge electrode used. Power increases with plate spacing due to the higher average voltage obtained with a wider spacing, while a nearly constant very low current is always produced.

It must be also emphasized that the beneficial effect of intermittent energisation on operation cost is associated, in same cases, with a parallel increase of ESP efficiency. Thus, operation of barb electrode is improved in these two ways with high-resistivity ashes, and also pipe-and-spike electrodes can attain some efficiency improvement. However, when intermittent energisation is coupled with low-power electrodes, like the twisted rod type, or with a very wide plate spacing, there is a drop in ESP efficiency. Also an unfavourable effect on efficiency is always produced under low-resistivity conditions when using intermittent energisation. Graphs in Figure 5 show the direct output of the PESP opacity monitoring system during a change of the energisation under high and low resistivity conditions, using the same discharge

electrode. The opacimeter readings plotted in this figure clearly indicate the response of the PESP to changes in the energisation and the previously commented effect of intermittent energisation on efficiency, positive with high resistivity ash and negative with low resistivity.
In relation to intermittent energisation results, it must be pointed out that measured reduction of power consumption in the PESP is higher than measured in the power plant full-scale precipitator. Differences between the control systems of both precipitators and some evidence of a poor adjustment of the full-scale unit power supply, make difficult to determine the real effect of scaling up on energy savings in coal ESPs. In any case, the need for a fine tuning of energisation control has become evident.

Attending to conventional rectified energisation results, a clear graduation of power consumption is established between different electrodes, in the expected way according with their electrical characteristics. Moreover, a substantial power reduction is always obtained with wider plate spacing, excepting for the barb electrode operating with high resistivity ash, where lower power consumption was measured for the spacing of 300 mm. In this situation, PESP operation was strongly restricted by dust resistivity thus imposing a certain reduction in operating voltage in order to control intensity excursions.

4.2 Results of HyColl tests

As main result, the HyColl has always achieved a particulate matter collection efficiency of 99.9% with independence of the operational conditions tested.

The effects of the different operational conditions in unit performance can be described by means of the following parameters:

- Pressure drop
- Pressure drop growth rate
- Time interval between cleaning cycles
- Number of cleaning cycles per day

The evolution of these parameters is shown in Table 5 for the two types of cleaning (continuous and discontinuous) and for different values of filtration velocity and active fields in ESP. The presented values correspond to a bag pressure drop maintained in the range from 1500 to 2000 Pa.

The discontinuous mode is much more effective for bags cleaning. Levels of pressure drop fall strongly below those obtained for continuous cleaning with the same filtration velocity and, therefore, higher velocities of filtration can be reached (50-60% higher). However, the pressure drop growth rates are also higher using the discontinuous cleaning type, as a consequence of the higher filtration velocity. Therefore, more frequent cleaning cycles are necessary to maintain pressure drop (up to 120 cycles per day, with 3 ESP active fields).

The pressure drop growth rates and the number of cleaning cycles per day are enlarged when the filtration velocity is increased following an approximately lineal relationship for each type of cleaning. These two parameters also grow when the number of ESP active fields is reduced. These relationships have been characterised for each set of operation conditions of the unit.

Examples of the evolution of the pressure drop when using continuous and discontinuous cleaning modes are shown in the Figures 6 and 7 respectively.

In the continuous cleaning mode, a progressive increase of pressure drop between consecutive cleaning periods is observed. This is associated to the formation of stable ash covers around the bags. After a certain period of time, cleaning cycles do not procure a reduction of pressure drop, it never decreases below the inferior limit for end cleaning set point. As a consequence, the cleaning period is too long due to the union of various cleaning cycles (Figure 6). This situation is very critical for the filter because of the dust accumulation in bags and the filtration capability reduction.

On the contrary, under discontinuous cleaning mode the effectiveness of the cleaning cycles is much higher, recovering low pressure drop levels after each cleaning cycle. Therefore, this mode is recommended for the design and operation of this type of filters.

A representative size distribution of particulate matter in the inlet and outlet of the HyColl is shown in Table 6 for tests considering different filtration velocity. It can be noticed that fractional efficiency for the finest particles (PM 2.5 fraction) grows when filtration velocity increases. (Figure 8).

In relation to metal determination tests, mean values of capture efficiency for metals in particulate matter are shown in Table 7. Removal level for all metals has been greatly satisfactory, derived from the high removal efficiency of fine particulate matter.

Just mercury has appeared in exit gases in a significantly high proportion. A capture efficiency of 40% has been achieved for mercury due to its considerable presence in vapour phase.

5. Concluding Remarks

5.1 ESP optimisation

Results clearly indicate the possibilities of ESP performance optimisation in a given application by adequately combining plate spacing, electrode geometry, and power supply, but different criteria are required as a function of energisation type and dust properties. Also a different approach may be required for the design of new units and for the retrofitting of existing ones.

The use of intermittent energisation appears as one of the most interesting aspects of coal precipitator improvement, although a precise adjustment of operational parameters is needed to ensure its best performance. The intermittent current is always able to strongly reduce ESP power consumption and, under adequate conditions, when dust of high resistivity is involved, it is also able to improve collection efficiency.

In the case of high resistivity ash, moderate and low-power electrodes present the best behaviour for a conventional narrow plate spacing (300 mm), whereas high-power electrodes tend to have some advantage when wide plate spacing (400 mm) is used. This advantage is more intense with intermittent energisation. Results also indicate that, in general, very wide plate spacing (500 mm) tends to produce lower ESP efficiencies than European design wide spacing.

In the case of low-resistivity ash, the conventional design - narrow plate spacing and high-power electrodes - appears as adequate. Results also indicate that some improvement in efficiency could be promoted by substituting this standard configuration for a correctly sized ESP using wide plate spacing and moderate-power electrodes. However, under low resistivity conditions continuous energisation is required to achieve a higher performance.

5.2. HyColl

The synergism between load reduction and precharge produced in the ESP fields and the use of high-tech micro-pore filtering media in the FF drives to a very high collection efficiency (>99.9 %), using an air-to-cloth ratio higher than those used in modern pulsed fabric filter collecting very fine particles. So, this technology overcomes the limitations of existing ESPs for accomplishing the new particulate matter emission limits at a lower investment cost than competing technologies.

In accordance with tests results, the industrial scale ESP retrofitting application of HyColl technology would require a total collection area about 60% of a conventional ESP plus 50% of a conventional FF. The resulting investment is therefore about 50% of that required for an ESP retrofitting to a complete FF. Operational cost of HyColl is about + 5 % of operational cost of a conventional FF.

In this sense, HyColl is a suitable best available technology (BAT) for the particulate matter collection in coal power plants and could be an appropriate and low cost add-on retrofit technology to existing plants with ESPs in order to accomplish the requirements of the new EU Directives.

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References

1. G.J. Grieco, "Understand, Solve Problems with ESP Wide Plate Spacing". Power, pp. 42-48, (August 1994).

2. R.R. Crynack, "Discharge Electrodes for Electrostatic Precipitators - A perspective". 9th EPRI Particulate Control Symp., Williamsburg, Virginia (October 1991).

3. M. Rea, V. Bogani, "Influence of the Electrode Geometry and of the Operating Characteristics on the Efficiency of Electrostatic Precipitators". 10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation, Washington, DC (April 1993).

4. E.C. Landman, et al., "Intermittent Energization with High Fly Ash Resistivity". 10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation, Washington, DC (April 1993).

5. C.A.J. Paulson, R. Morrow, A.J. Prokopiuk, "The Performance of a Pilot-Scale Electrostatic Precipitator Using Continuous, Intermittent and Pulsed Energization". 10th Particulate Control Symp. and 5th Int. Conf. on Electrostatic Precipitation, Washington, DC (April 1993).

6. E.H. Weaver, F.A. Gallo, S. Mecheri, "A Comparison of Several Generations of Electrostatic Precipitator High Voltage Control Systems". 9th EPRI Particulate Control Symp., Williamsburg, Virginia (October 1991).

7. J.S. Chang, "Next generation integrated electrostatic gas cleaning systems". Journal of Electrostatics, v 57, n 3-4, p 273-291 (2003).

8. L. Cañadas, B. Navarrete, P. Ollero, L. Salvador, “Parametric Testing of Coal Electrostatic Precipitator Performance”. Environmental Progress, v. 16, n 2., p. 98-105 (1997).

9. EPA Stationary Source Sampling Methods. "Method 17 - Determination of particulate emissions from stationary sources (in-stack filtration method). Rev. 2. 7/91".

10. EPA Stationary Source Sampling Methods. “Method 29 - Determination of metals emissions from stationary sources Rev. 2. 7/91”.

Dimensions of precipitation chamber	
Length (m)	12.6
Width (m)	2.5
Height (m)	2.6
No. of electric fields	3
Dimensions of fields	
Effective length (m)	2
Effective height (m)	2.2
No of gas passages	3 to 7
Plate spacing (mm)	200 to 500
No. of electrodes per gas passage	4 to 12
Operating conditions	
Gas flow (m^3/h)	9,000 to 20,000
Precipitation area (m^2)	79.2 to 184.8
SCA (m^2/m^3/s)	14 to 74
Gas velocity (m/s)	0.8 to 1.8
TRs	
Peak voltage (kV)	110
Max. effective voltage (kV)	78
Max. effective intensity (mA)	42
Energisation control	Castlet MCS

Table 1. Pilot ESP Design and Operating Conditions

Parameter	**Levels**		
Coal	Coal A (High resistivity ash)	Coal B (Low resistivity ash)	
Electrode	barb wire	pipe-and-spike	twisted square rod
Plate spacing	300 mm	400 mm	500 mm
Gas velocity	0.8 m/s	1.1 m/s	1.3 m/s
ESP energisation	continuous rectified current	Intermittent (semipulsed) rectified current	

Table 2. ESP tests Matrix

Property	**Coal A**	**Coal B**
Ultimate analysis (wt %, d.b.)		
C	74.3	79.6
H	4.1	5.1
N	1.8	1.5
S	0.7	0.8
O	6.4	7.3
Ash	12.7	5.7
Moisture (wt %)	8.0	11.3
HHV (kcal/kg, d.b.)	6800	7600
Ash composition (ASTM D-3682-78, wt %)		
SiO_2	39.6	61.3
Al_2O_3	33.1	18.1
Fe_2O_3	2.8	9.6
CaO	8.5	2.5
MgO	2.5	2.3
Na_2O	0.4	1.3
K_2O	0.8	2.4
MnO_2	0.06	0.06
TiO_2	2.1	0.9
P_2O_5	1.4	0.3
SO_3	6.1	0.7
Fly ash in-situ resistivity (Ohm·cm)	10^{12} - 10^{13}	10^{8} - 10^{9}

Table 3. Coal characteristics

Parameter	**Levels**			
Air to cloth ratio	5.5 ft/min	7.5 ft/min	8.5 ft/min	9.5 ft/min
ESP active fields	0	1	2	3
Bags pressure drop	1000 Pa	1500 Pa	1750 Pa	2000 Pa
Cleaning parameter	HPLV	IPIV	LPHV	
Cleaning mode	Continuous	Discontinuous		

Table 4. HyColl tests Matrix

Cleaning mode	ESP active fields	Filtration velocity (ft/min)	Pressure drop growth rate (mmH_2O/min)	Number of cleaning cycles per day
Discontinuous	3	8.61	3.25	117
	2	8.02	3.97	143
	1	7.51	4.58	165
Continuous	3	5.48	1.18	43 *
	3	4.98	1.10	40 *
	3	4.59	0.61	22 *
Continuous (only bag filter)	0	6.35	4.04	145
	0	5.57	3.44	124

** After some hours of operation, cleaning was unable to reduce pressure drop to the desired value of 1500 Pa.*

Table 5. Global results of HyColl tests under modifications of gas filtration velocity and ESP active fields

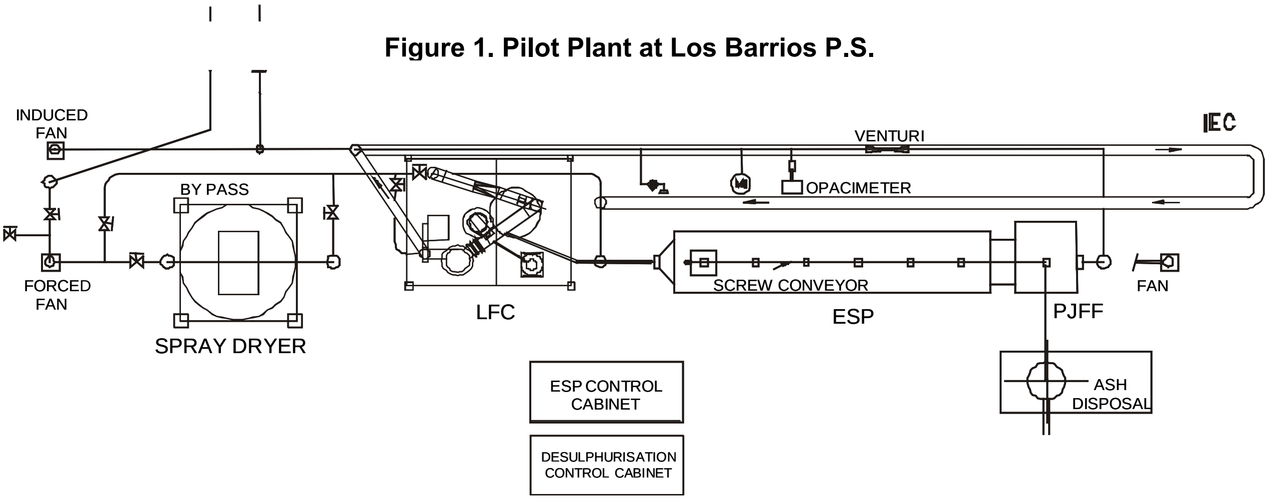
Filtration velocity (ft/min)	Location	Content by size (%)		
		Dp > 10μm	10μm > Dp > 2.5μm	Dp < 2.5μm
5.4	INLET	85.4	12.5	2.1
	OUTLET	20.0	53.3	26.7
6.7	INLET	83.0	14.7	2.3
	OUTLET	6.3	12.5	81.3

Table 6. Size distribution for HyColl inlet/outlet samples

Arsenic	Cadmium	Chromium	Mercury	Nickel	Lead
99.4%	>99.9 %	99.5%	40 %	99.1%	99.0%

Table 7. HyColl capture efficiency for metals

Figure 1. Pilot Plant at Los Barrios P.S.



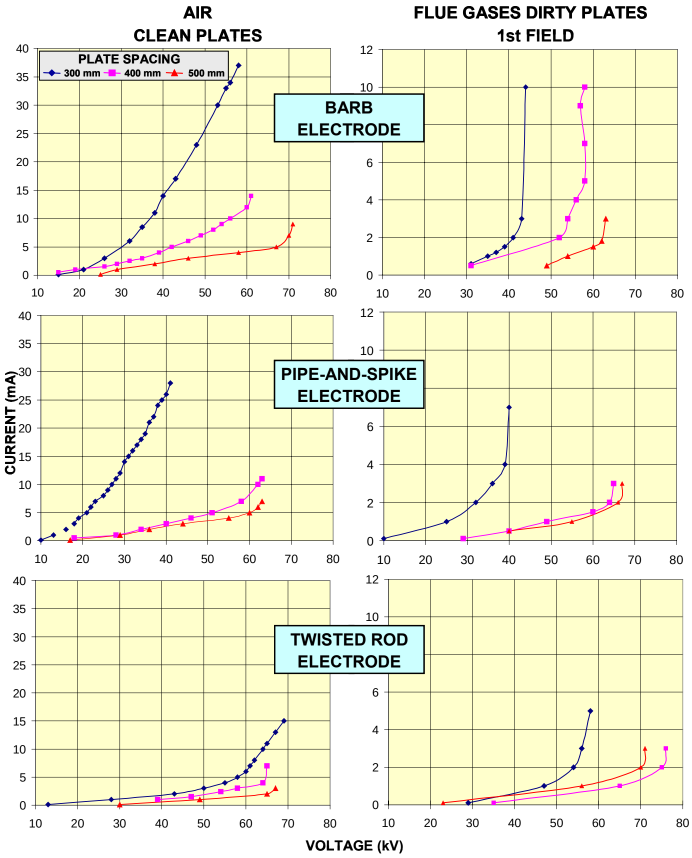


Figure 2. Voltage-current curves of ESP electrodes

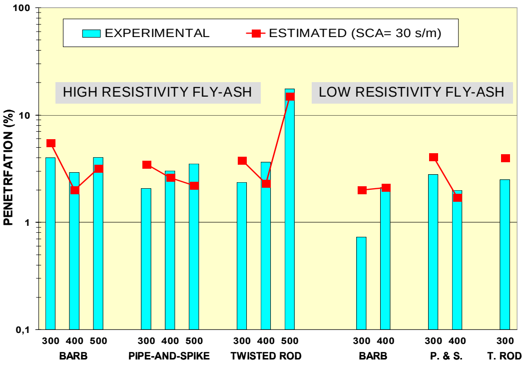


Figure 3. Effect of ESP configuration on efficiency

Figure 3. Effect of ESP configuration on efficiency

Figure 2. Voltage-intensity curves of ESP electrodes

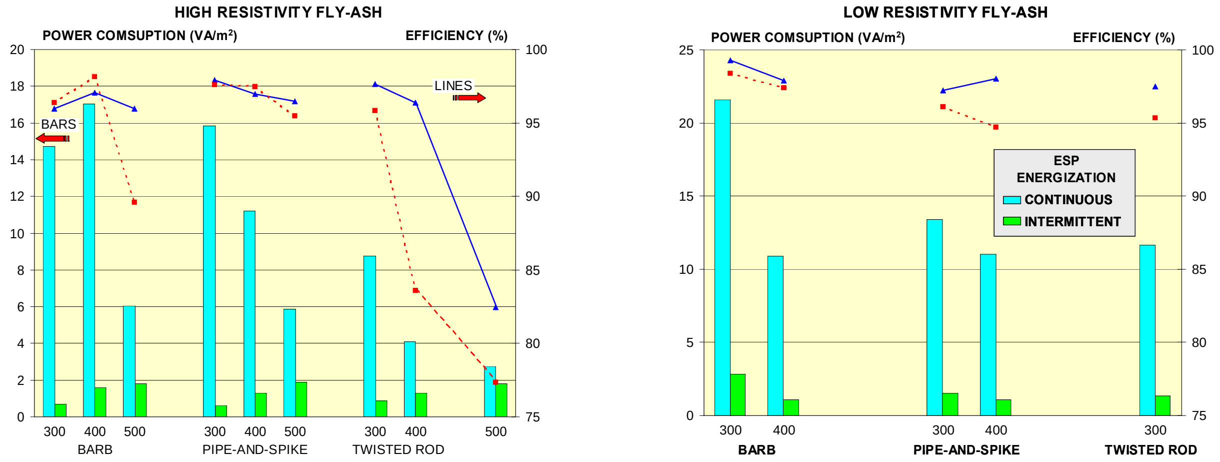


Figure 4. Effect of energisation on ESP performance

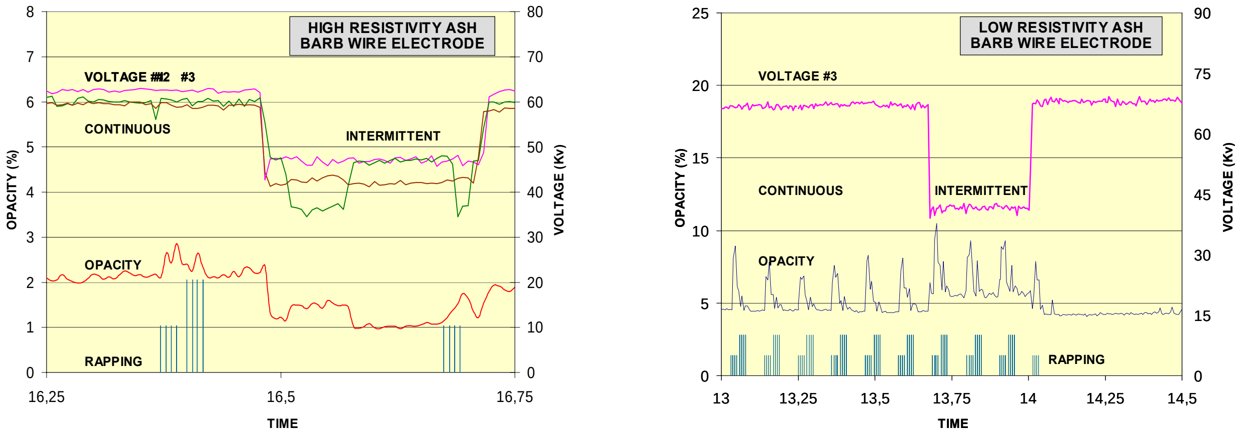


Figure 5. Pilot ESP output under different energisation

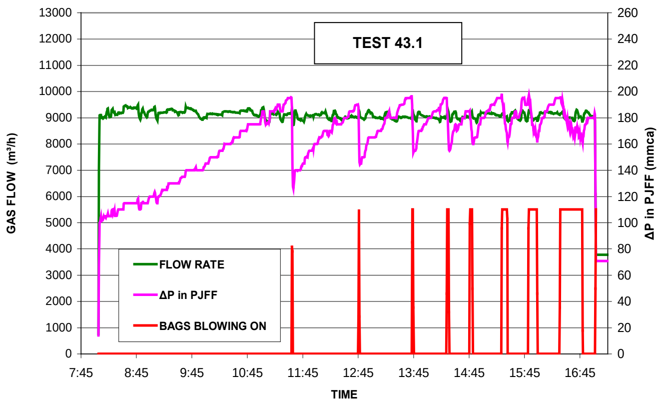


Figure 6. Continuous cleaning in HyColl
(3 active ESP fields)

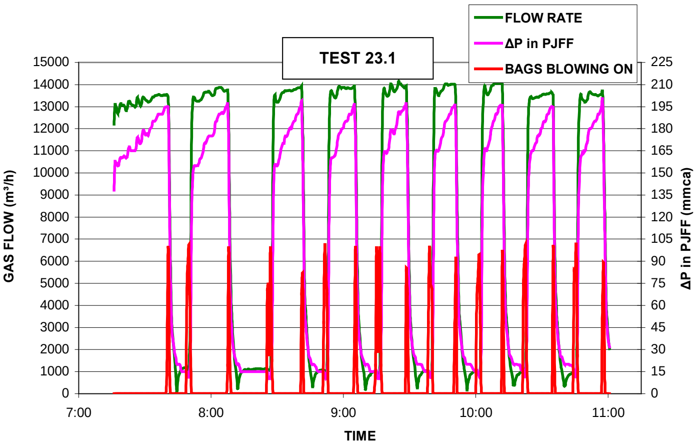


Figure 7. Discontinuous cleaning in HyColl
(3 active ESP fields)

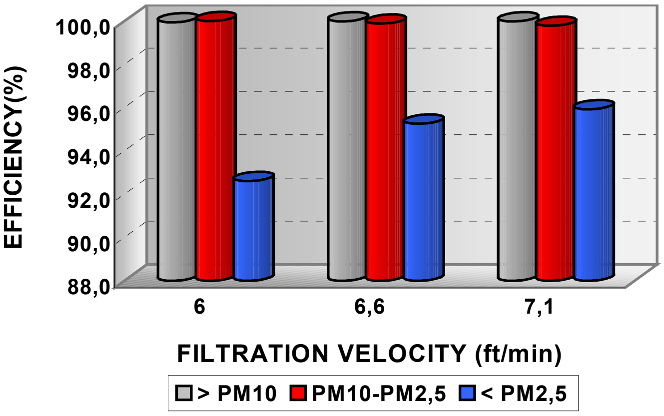


Figure 8. HyColl particulate matter removal efficiency versus filtration velocity for different particle sizes