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INVESTIGATIONS ON FLY ASH RESISTIVITY: DEVELOPMENT OF EMPIRICAL RELATIONS BASED ON EXPERIMENTAL MEASUREMENT

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ABSTRACT
Fly ash resistivity is a single parameter which has got significant impact over sizing and performance of Electrostatic Precipitator (ESP) in coal based thermal power plants. A fly ash resistivity measurement facility has been set up at IIT Delhi with the support of National Energy Technology Laboratory (NETL), USA and USAID-India. The fly ash samples from different power plant are being collected by CenPEEP, NTPC and supplied to IIT Delhi for measurements. The experiments were conducted for the measurements of electrical resistivity over a wide range of temperatures (90-455) ^{0}C as per IEEE standards. Around 250 samples obtained from different power plants in India, have been tested. Empirical relations developed by Bickelhaupt, which are based on the chemical composition of fly ash for calculating the electrical resistivity are used to calculate as theoretical value for given experimental conditions. Comparisons between fly ash resistivity obtained from experiments and theoretical values show significant differences between the two values especially at low temperatures (90-160 ^{0}C), where surface conduction is important. This is due to the different chemical compositions of ash/fly ash obtained from the coals used in power plants in India and USA. New empirical relations based on chemical compositions, generated in typical Indian power plants have been developed to calculate electrical resistivity at the temperature and moisture corresponding to actual conditions to ESP. These relations provide better agreements with experimental values.

1. INTRODUCTION:

The production of coal and its use as a source of electricity play a vital role in social and economic development in many regions of world. The market share of coal in electricity generation in developing countries is around 45% at present and is expected to rise up to 47% in 2030 [1]. China and India have large plants of expanding coal-based power plants. At present India has got 61,175 MW installed coal based power capacity which is expected to rise 1,14,500 MW by the year 2012 [2]. Fly ash emitted by the coal-based power plants is serious air pollutions in and around the power plants. The collection of fly ash in electrostatic precipitators has been most commonly used method for cleaning the gas from power boilers. In order to meet the stringent emission levels from power plant, it is necessary to have knowledge of the properties of fly ash, sizing and operation of ESP. Retrofit methods can be applied to an ESP depending on the electrical and chemical properties of the fly ash.

The design and operation of ESP depends largely on the properties of coal burned and fly ash generated in the boilers. The properties of coal used in difference plants across India vary widely. In many of the power plants, the ash contents of coal are high up to 45%, and the coals have low calorific values (3500-4200) Kcal/kg. As a result Indian coal generates about 6 to 7 times more ash to collect compared to U.S. or European coal for similar electricity generation. Besides, low sulfur content (=0.5%) result in the resistivity is (100-1000) time higher as compared to desired range of resistivity (1×10^{7} - 2×10^{10}) ohm-cm. for efficient ESP.

At the high resistivity of the order of 10^{12} ohm-cm or more, typically found in Indian coals with low sulfur contents, the ESP collection efficiency is poor, requiring very large plate collector area to achieve higher efficiencies. A series of experiments have been performed to study the variation of fly ash resistivity with temperature for low sulfur coals and it was confirmed that Indian fly ash has higher resistivity as compared to those of western coals and is therefore, difficult to precipitate[3, 4]. The reason for low precipitation is the generation of back corona near the collecting electrodes even at very low current densities.

The electrical resistivity depends on its chemical composition, temperature, and moisture. A number of empirical relations have been developed to predict the electrical resistivity of fly ash as a function of various parameters mentioned earlier [5, 6]. A set of correlations for predicting fly ash resistivity based on the composition and the coal analysis have developed by Bickelhaupt [7,8] and are widely used in USA, primarily for those fly ashes which are based on western coals. Southern Research Institute Birmingham USA is also using similar relations [9] for evaluating the resistivity. In India, however, there are varieties of coal used in different power plants across the country. They differ significantly from those used in USA. The composition of fly ash is too different from those generated in power plants in USA. The objectives of the present studies are:

(a) To measure resistivity of representative fly ash samples from different Indian power plants and compare the experimental results with those obtained from Bickelhaupt relations.
(b) To develop mathematic model to predict the fly ash resistivity for Indian coals, in case there is significant departure from Bickelhaupt relations
(c) To study the effect of NH_3 dosing and sodium conditioning of ash on the resistivity of fly ash. The samples have been obtained from the Indian power plants, wherever such experiments have been performed to improve the collection efficiency of ESP.

2. EXPERIMENTAL ARRANGEMENT AND PROCEDURE:

An experimental test arrangement was set up per IEEE standard criteria and guidelines [10] for the fly ash resistivity measurements as shown in fig.1. The current across the fly ash layer under test is limited to 2×10^{-5} amp/cm^2 to avoid the ohmic heating of the fly ash sample. The test apparatus includes four electric resistivity test cells enclosed in such a manner that the test cells are housed in a thermally controlled chamber so that resistivity can be determined at temperature range of 90-455 ^{0}C. A dc high voltage power supply was used to impress the required magnitude of electric field strength. The environment was maintained as per the standard. The environmental water concentration was introduced by bubbling a portion of dry gas through distilled water maintained at a selected temperature in a thermostatically controlled water bath. It was 9% by volume at the specified temperature in the present study. The oven is capable of operating in the desired temperature range, within 0.01 ^{0}C accuracy. The resistivity test cell has parallel plate construction made from SS 304 steel. The resistivity cell current was measured using a sensitive electrometer capable of reading current in the range o 10^{-3} to 10^{-11} amp., with an accuracy of ± 2% of the full-scale reading. Fly ash samples were prepared in accordance with the IEEE standard and placed in the test cell in a grounded environmental chamber. The upper electrode is gently placed on the top of ash with a defined pressure. The oven is started and once the desired temperatures are reached, the readings are taken for the temperature, voltage and current using the instrumentation provided in the test facility. The fly ash resistivity, ρ is calculated from standard relation:

$$r = \left(\frac{V}{I}\right)\left(\frac{A}{l}\right)$$

Where, V and I are the voltage and current across the fly ash sample, l and A represent the thickness and area of cross-section of sample of fly ash cell. The resistivity is calculated for more than 250 different fly ash samples from Indian coal fired thermal power plants for the temperature range of 90 ^{0}C to 460 ^{0}C. However, 20 representative samples have been selected whose chemical composition is known, for the development of model for ash resistivity.

3. EMPIRICAL RELATIONS FOR PREDICTION OF FLY ASH RESISTIVITY:

Based on the chemical compositions of representative fly ash samples, shown in table 1, the electrical resistivity has been calculated using Bickelhaupt [11] correlations, which are described the following section:

(a) Bickelhaupt relations:

Bickelhaupt [11] proposed correlations to calculate the fly ash resistivity from the results of coal and the fly ash analysis. The correlation fly ash resistivity in terms of volume resistivity, surface resistivity and adsorbed acid resistivity is:

The volume resistivity is:

$$\rho_V = \exp\left[(-1.8916 \ln X - 0.9696 \ln Y + 1.237 \ln Z + 3.62876) - (0.069078)E + \left(9980.58/T\right)\right] \quad (1)$$

The surface resistivity is:

$$\rho_S = \exp\left[27.59774 - 2.233348 \ln X - 0.00176W - 0.069078E - 0.00073895W(\exp)\left(2303.3/T\right)\right] \quad (2)$$

The adsorbed acid resistivity is:

$$\rho_a = \exp\left[59.0677 - 0.854721\ CSO_3 - 13049.47/T - 0.069078\ E\right] \quad (3)$$

For Z > 3.5% or K < 1.0 %

The resultant resistivity is:

$$\frac{1}{\rho_{vsa}} = \frac{1}{\rho_{vs}} + \frac{1}{\rho_a} \quad (4)$$

where , $$\frac{1}{\rho_{vs}} = \frac{1}{\rho_v} + \frac{1}{\rho_s} \quad (5)$$

(b) Proposed correlation for fly ash resistivity of Indian coal

The Bickelhaupt model in equations is used to calculate the resultant resistivity for three fly ash samples of Indian power plants. Comparison between calculated and experimental fly ash resistivity values for these samples is presented in figures 2-8. It can be observed that Bickelhaupt model results differ appreciably from experimental values in the lower temperature range (90-160 ^{0}C). It may be due to significant difference in concentration of elements like sulfur, lithium, sodium and moisture contents as well as alumina plus silica components among the Indian and US coals. The sulfur concentration in coal regulates the adsorbed acid resistivity. Keeping these points in view, the fly ash resistivity for Indian coals was re-calculated in terms of surface and volume conduction. Since the concentration of sulfur is very less in Indian coals, it is worthwhile to assume that very little or zero adsorbed acid conductivity is present. The negligible adsorption of SO_3 conduction may also be due to formation of glassy alumina-silicate surface that hinders the adsorption of SO_3 on the fly ash surface. The total conduction in fly ash is thus assumed entirely due to surface and volume conduction. The Bickelhaupt expressions for surface and volume resistivity are therefore, modified for the Indian coals. Regression procedure based on the Marquardt-Levenberg algorithm is used to find the coefficients of the independent variables of volume and surface resistivity that give the best fit between the proposed correlations and the experimental data. The modified correlation for the volume and surface resistivity is:

Correlation for the volume resistivity:

$$\rho_V = \exp\left[(-a_v \ln X - b_v \ln Y + c_v \ln Z + d_v) - (e_v)E + \left(g_v/T\right)\right] \quad (6)$$

Correlation of the surface resistivity

$$\rho_S = \exp\left[a_s - b_s \ln X - c_S W - d_s E - e_S W(\exp)\left(g_S/T\right)\right] \quad (7)$$

The resultant resistivity is:

$$\frac{1}{r} = \frac{1}{r_V} + \frac{1}{r_S} \quad (8)$$

4. TO STUDY THE EFFECT OF NH_3 DOSING OF FLUE GASES AND SODIUM CONDITIONING OF ASH:

Fly ash sample were collected from power plant no.2 and power plant no.3 [12]. In power plant no.2, the ammonia dosing to flue gas was varied and the inlet and outlet dust loading were measured. The fly ash samples were collected for no dosing and varied amount of NH_3. The experimental measurements of electrical resistivity were made as per IEEE standards. Similarly fly ash samples were collected from power plants no.3 for untreated and treated with sodium conditioned coal before feeding to boiler. Corresponding data for dust loading was also available. In the following sections we describe investigations related with fly ash resistivity.

(a) Investigation on electrical resistivity due to dosing of ammonia to flue gases.

Resistivity measurement was made on the fly ash samples between the temperatures (90-455) ^{0}C with 9% moisture. Measurements were made on ascending and descending mode of temperatures for different amount of dosing. The following observations are made:

(i) There are significant changes in resistivity during ascending mode between no dosing and dosed samples.

(ii) These changes are more pronounced at lower temperatures (=200 ^{0}C), where surface conduction dominates through fly ash deposited on the collecting electrodes.

(iii) There is significant drop in resistivity corresponding to enhanced value of migration velocity, collection efficiency of ESP and much lower out let emissions.

(iv) The difference in resistivity between the dosing and no dosing conditions reduce as one goes to higher temperatures.

(v) There is very little difference in resistivity between no dose and dosed fly ash samples in descending mode.

One may conclude from these observations that ammonia dosing enhances surface conduction (=200 ^{0}C), thereby reducing the resistivity by about an order of magnitude. As a result, collection efficiency of ESP improves and emission levels drop drastically (from 166 to48 mg/Nm^3). As the temperature raise (=200 ^{0}C), the effect of NH_3 is barely observed. This also explains why there is very little difference between dosed and undoes samples of fly ashes in descending mode.

(b) Effect of sodium conditioning:

Fly ash samples were collected from power plant no.2. Sodium sulphate salt was added to coal mass in such a manner as to increase the sodium oxide content of fly ash by 0.5% [12]. Fly ash samples from treated and untreated conditions were obtained and resistivity measurements were made as per IEEE norms. Based on the experimental investigations, the following observations may be made:

(i) There is significant decrease in resistivity at all temperatures in the range 90-455 ^{0}C.

(ii) This decrease of resistance correspond to enhance collection efficiency of ESP resulting in drastic reduction in emission levels [12].

(iii) There is enhanced electric conduction due to increased conduction of sodium concentrations both at lower (surface conduction) and higher (volume conduction) temperatures. At operating temperatures of ESP (140-180) ^{0}C the resistivity is decreased by an order of magnitude resulting in higher migration velocities.

5 RESULTS AND DISCUSSION:

Using the above proposed correlations (7) and (8), the surface (?$_s$), the volume (?$_v$) and hence the overall resistivity (?) of the fly ash particles were calculated for different experimental conditions. The overall calculated and experimental fly ash resistivity has been plotted for different fly ash samples in Figs. 2 - 8. For the sake of comparison, the values obtained from Bickelhaupt model are also shown in these figures. It can easily be observed that a much better agreement has been obtained between the experimental and calculated values, using proposed model in the lower temperature range (=160^{0}C). The agreement at higher temperature range is also comparatively better by using the expressions developed by Bickelhaupt for volume conduction. As the working range of electrostatic precipitator is in the range 130-180^0 C, the relations developed in the present studies for surface conduction are more useful.

More experimental investigations are required on the large number of fly ash samples from various Indian power plants, to develop an accurate model and predict the fly ash resistivity, for various operating conditions. Detailed investigations are required to predict the effect of NH_3 dosing of flue gas and sodium conditioning of coal ash on the electrical resistivity of the fly ash for developing an appropriate model.

From the present investigation, it appears that the amount of sulphur available in the flue gas is very little, to have any significant acid conduction. This explains the problem of encountering the high fly ash resistivity even at lower operating temperatures in Indian ESP. The situation is quite different for the other coals, where the sufficient amount of sulphur is available resulting in lower resistivity and hence Bickelhaupt model is more useful for such coals.

NOMENCLATURE:

A electrode phase area (cm^2)
CSO_3 concentration of CSO_3 (ppm, dry)
E applied electric field (kV/cm)
I measured current (amperes)
K potassium percent atomic concentration
l ash layer thickness (cm)
T absolute temperature (K)
V applied d.c. Potential (volts)
W moisture in flue Gas (Volume %)
X Li + Na, Percent Atomic Concentration
Y Fe, Percent Atomic Concentration
Z Mg + Ca, Percent Atomic Concentration

Greek Letters:
r = Resistivity (ohm-cm)

Subscripts:
v volume
s surface
a adsorbed Acid

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REFERENCES:

[1] E coal. The quarterly newsletter of World coal institute Vol54, July2005

[2] High light 2004, "Parivesh", published by CPCB, Ministry of Environment & Forest Feb2005.

[3] Chandra, A., Kumar, S., and Kumar Sanjeev, .Investigations on fly ash resistivity of varieties of coals used in Indian power plants, Proceeding, 9th International Conference on Electrostatic Precipitation, Mpumalanga, South Africa pp **B-05**, 2004.

[4] Chandra, A., Sabberwal, S.P., & Mukherjee, A.K.). Performance evaluation of an ESP unit using low grade coal. *6th International Conference on Electrostatic Precipitators, Budapest*, (pp209-214), 1996.

[5] White H.J., *Industrial electrostatic precipitation*. Addison Wesley, Reading MA., 1963.

[6] Chandra, A., Sharma, P.K., Sanjeev, K., & Kumar, S.. Effect of fogging, flue gas conditioning and sodium dosing of coal on fly ash Resistivity, an experimental investigation. *International Conference on Energy and Environment: Strategies for Sustainable Development, New Delhi*, pp418-423, 2004.

[7] Bickelhaupt, R.E. Electrical volume conduction in fly ash. *Journal of Air Pollution Control Association*, **24,** 251-255, 1974.

[8] Bickelhaupt, R.E. Surface Resistivity and the chemical composition of fly ash. *Journal of Air Pollution Control Association,* **25**, 248-152., 1975.

[9] Dismukes, Edward. B, "Conditioning of fly ash with sulfur trioxide and Ammonia." Report No. EPA-600/2-75-015, Southern research Institute, Birmingham. Alabama USA. ,1975.

[10] IEEE Standard criteria and guidelines for the laboratory measurement and reporting of fly ash Resistivity. *IEEE – Standard 548.*, 1991.

[11] Bickelhaupt, R.E. A technique for predicting fly ash Resistivity. US EPA *Report No. EPA*- 600/7-79-204, 114 pp.,1979.

[12] Merchant, G.H. Jr., "Evaluation of Sodium Conditioning, Water Fogging and Coal Washing for Environmental Performance Improvement of ESP's at BALCO Captive Power Plant" Research Report under USAID-India: Green house Gas Pollution Prevention Project, Sept. 1999.

Table:1 Chemical compositions of the typical fly ash samples (weight percent as the oxide)

Sample no.	Na_2O	K_2O	MgO	CaO	Fe_2O_3	Al_2O_3	SiO_2	TiO_2	P_2O_5	SO_3
5	0.13	1.10	0.88	1.13	5.21	31.60	55.45	1.91	0.18	0.38
13	0.09	0.59	0.54	1.63	4.22	35.95	52.97	2.19	0.10	0.55
29	0.06	0.64	0.26	1.43	5.08	28.24	61.33	2.01	0.07	0.25
37	0.13	0.48	0.45	2.97	7.56	24.76	60.20	1.59	0.06	0.20
56	0.15	1.34	0.74	2.57	6.58	31.03	51.61	2.60	0.13	0.23
64	0.15	1.04	0.73	2.30	5.46	23.70	59.64	1.90	0.9	0.03

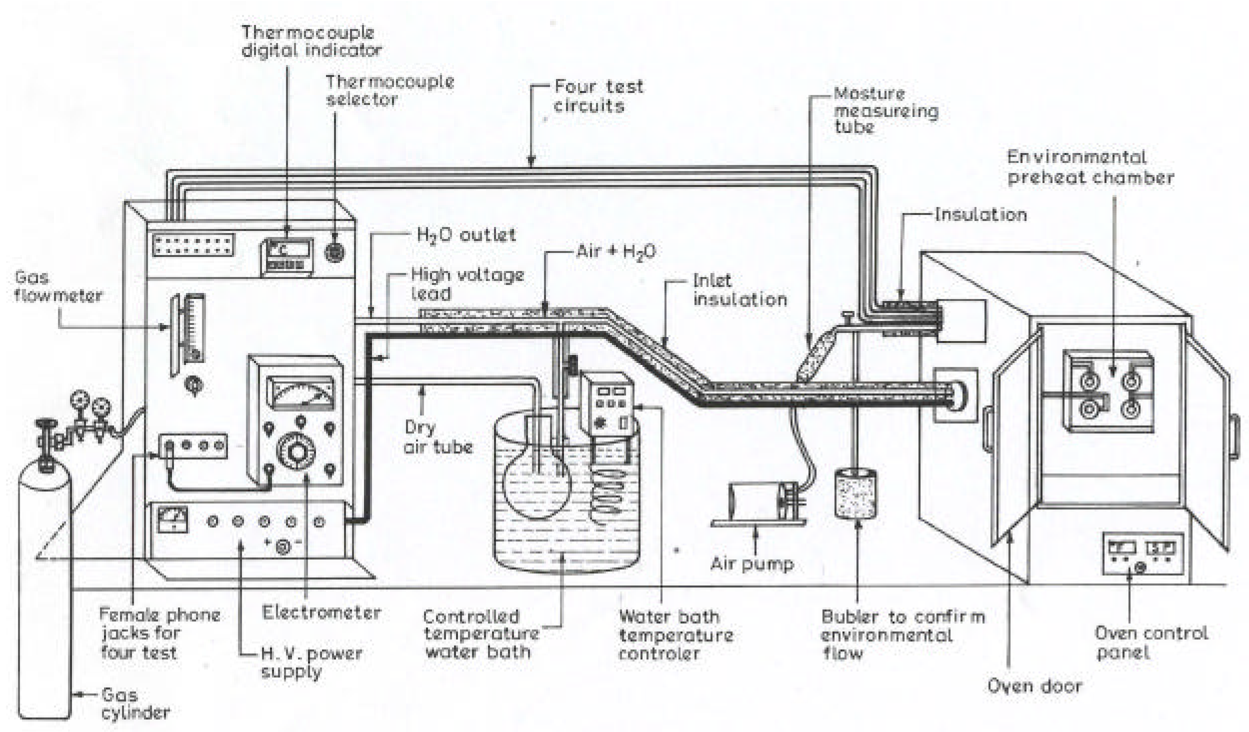


Fig 1. Schematic diagram of ash resistivity measurement setup at IIT Delhi

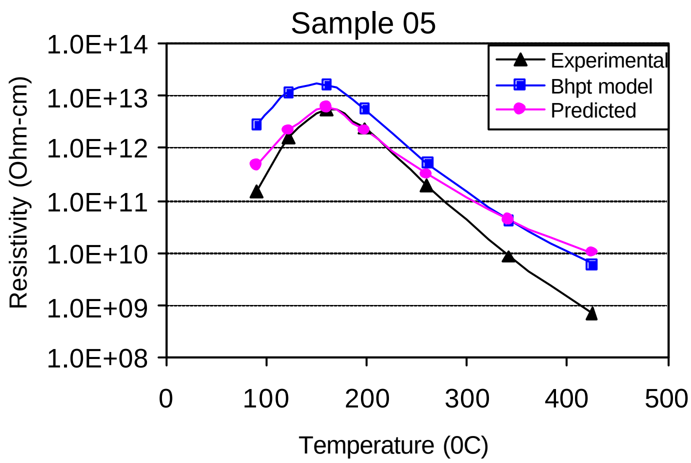


Fig 2

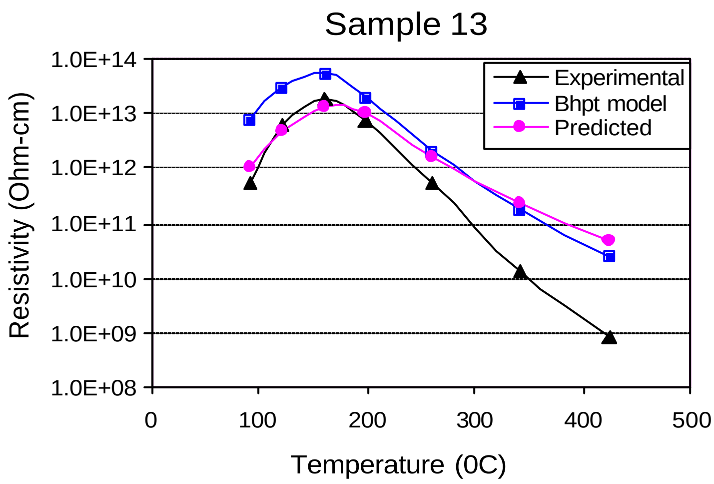
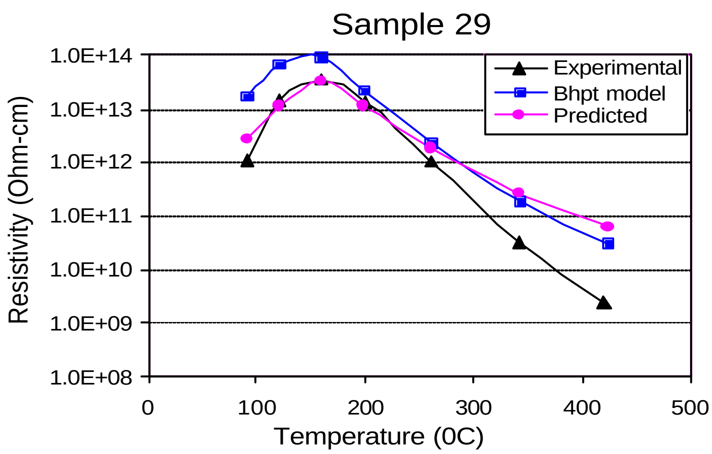


Fig 3



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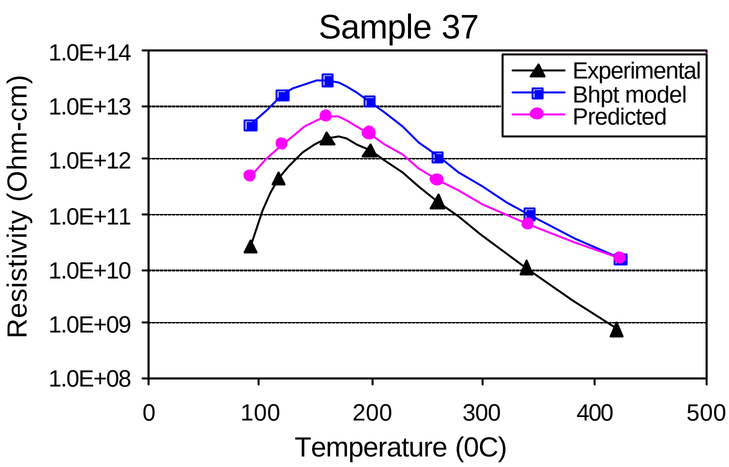

Fig 5

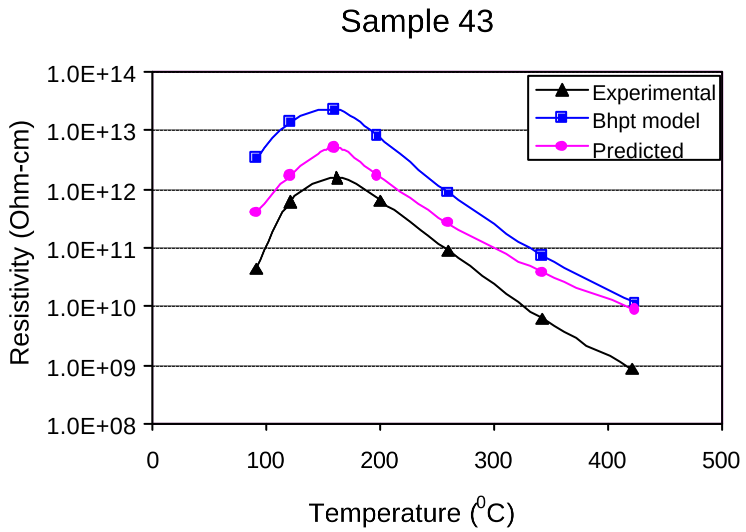

Fig 6

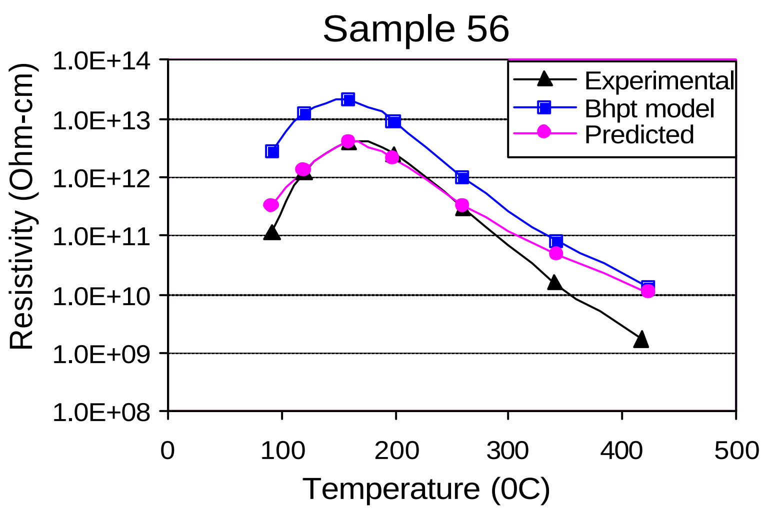

Fig 7

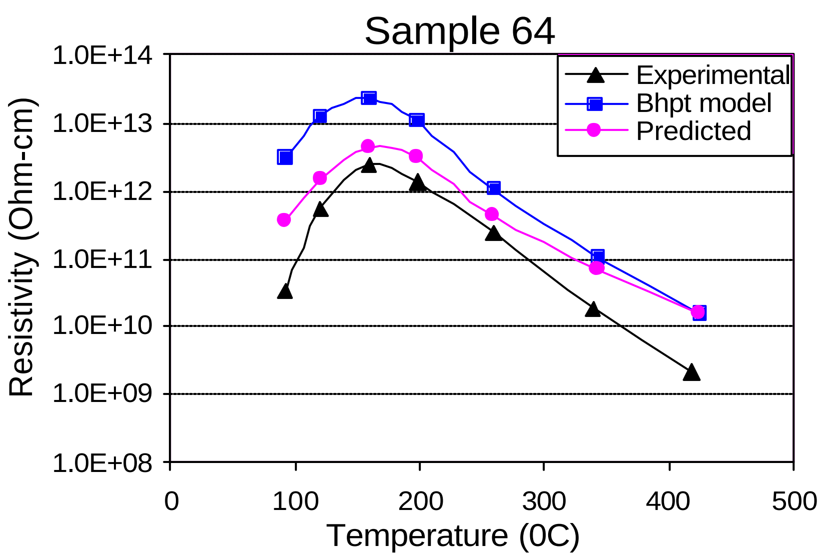

Fig 8