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## PREFACE

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# WATER ADSORPTION EQUILIBRIA ON MICROPOROUS CARBONS

## 1. INTRODUCTION

Microporous carbons and impregnated microporous carbons are used in filter systems for military air purification applications. Activated carbon is particularly well suited to this task because it has a high capacity and broad range of pore sizes. Water adsorption in carbon filters is important because water vapor is often present in higher concentrations than any other gas constituent. The filters must operate over the range from essentially dry conditions up to 100% relative humidity. For many toxic and noxious vapors the protective capabilities of the activated carbon filter are reduced at higher relative humidities, while at very low humidities the impregnants are often ineffective. A better understanding of the effect of adsorbed water vapor on filter performance is critical for improved filter design. The equilibrium adsorption isotherm of water vapor on activated carbon provides the best means of evaluating the extent and the mechanism of water adsorption.

The most extensive studies of water vapor adsorption on activated carbons and charcoals were conducted over thirty years ago. These studies<sup>1-6</sup> used the theory of capillary condensation to determine the pore volume distribution on the carbon from the water isotherm. They showed that with the proper parameters, the water vapor isotherm could be used to predict the same pore volume distribution as the more widely accepted nitrogen adsorption method developed by Barrett.<sup>7</sup> Subsequent to these initial studies, very little research has been reported on refinements of this technique or the measurement of water isotherms on activated carbons. Juhola<sup>8,9</sup> has recently reviewed this area maintaining his belief that capillary condensation is the dominant mechanism for water vapor adsorption on activated carbons.

Dubinin and Serpinsky<sup>10,11</sup> have proposed a theory of water adsorption on activated carbon. They developed a mathematical expression which describes the quantity of water adsorbed using an equilibrium reaction with surface oxygen complexes. It is proposed that this model would apply up to a relative humidity of 60%. Barton and Evans<sup>12-14</sup> studied the oxidation of activated carbon and its effect on adsorption of water. Their results were analyzed with respect to the Dubinin expression. This revealed that the parameters could not be correlated over a wide range of oxidation conditions, leaving in doubt the theory that the water isotherm on activated carbon is controlled by surface oxide sites. Juhola<sup>15</sup> has also published studies showing that surface oxide sites do not influence water adsorption on activated carbons.

A conceptually simple model for a general adsorption isotherm was proposed by Sircar.<sup>16,17</sup> He derived an extensive adsorption model in order to account for the effects of physical adsorption and capillary condensation in microporous adsorbents. This was the first isotherm model to incorporate a quantitative description of capillary condensation. Implementation of the isotherm required evaluation of six parameters, where each parameter had physical significance.

Water vapor adsorption on activated carbons exhibits several unique characteristics. The isotherm of water is, in general, a type V by the Brunauer classification. It exhibits an unfavorable region at low relative humidities followed by a dramatic increase in adsorption and finally a plateau at the highest relative humidities. This behavior is different from vapors whose adsorption can be characterized by pore filling models which suggests that another mechanism is responsible for the behavior of water adsorption on activated carbons. Another unique aspect of water adsorption on activated carbon is the presence of a large hysteresis loop indicating that the amount adsorbed depends on the past exposure conditions of the carbon. The theories to describe hysteresis in microporous adsorbents and the experimental evidence to support each theory have been reviewed by Everett<sup>18</sup>. The most widely accepted theory is the so called "ink bottle" theory. It is assumed that in the desorption process small pores constrict the openings to larger pores such that a large amount of water remains adsorbed until the partial pressure of water is reduced to a value which corresponds to that of the smaller pore radius.

At present there is not a water vapor adsorption isotherm which correctly accounts for all the observed behaviors on activated carbon. Neither the Dubinin-Serpinsky, nor the Sircar equations provide any explanation for hysteresis. It appears that, based on the findings by Juhola, the development followed by Sircar best represents the adsorption behavior over the entire relative pressure range. One obvious difficulty with the Sircar isotherm is that it implies that capillary condensation occurs in pores which can be characterized by a single pore size distribution. This does not seem realistic for activated carbons which possess bimodal or trimodal pore size distributions consisting of micropores, mesopores, and macropores. It seems justified then to extend the work of Sircar in order to incorporate a modification to account for more than one distribution of pore sizes.

Efforts have been made to modify existing pore filling models in order to obtain an expression which would correlate the data for water adsorption on activated carbon. This was considered because the Sircar model was not convenient to apply in numerical applications. A form of a modified Antoine equation proposed, by HacsKaylo and LeVan<sup>19</sup>, was considered because of the success reported in the

correlation of pore filling mechanism type isotherms. The advantage of this correlation was that unlike many pore filling isotherms it predicted reasonable behavior at the limits of zero loading and saturation. The physical significance of the parameters in this correlation was not established.

The present study involved measuring water vapor adsorption on several carbon samples. Both temperature effects and hysteresis were considered. The resulting data was then analyzed using the proposed isotherms.

## 2. THEORY

Sircar<sup>16,17</sup> developed a correlation for vapor phase adsorption which included contributions of physical adsorption and capillary condensation. This model was derived from the assumption that the pore diameters in the particle could be described by a single gamma distribution. The use of this distribution function can be extended to microporous adsorbents having a bidisperse pore size distribution. The mathematical development follows from the work of Sircar.

The Kelvin equation provides a basis from which to build a model to describe capillary condensation in microporous adsorbents. It can be written as follows:

$$r = \frac{-2\sigma V_L \cos\theta}{RT \ln \left( \frac{p}{p_{\text{sat}}} \right)} \quad (1)$$

Where  $r$  is the pore radius,  $V_L$  the molar volume of the adsorbed phase,  $\sigma$  the adsorbate surface tension,  $\theta$  the contact angle between the adsorbate and the adsorbent,  $p$  the partial pressure of the vapor,  $p_{\text{sat}}$  the vapor pressure, and  $T$  the temperature.

The Sircar isotherm is modified by beginning with the assumption that the adsorbent possesses a distribution of micropores with micropore volume,  $V_m$ , and a distribution of mesopores with volume,  $V_M$ . (Macropore adsorption is not considered because the Kelvin equation for water indicates that macropores greater than 50 nm in diameter would require a relative humidity close to 97%.) The sum of  $V_m$  and  $V_M$  is taken as  $V_T$ , the total pore volume available for adsorption per unit weight of carbon. Following the notation of Sircar,<sup>16</sup>  $V_T$  can be obtained by integrating the pore volume distribution functions over the volume of the pellet.

$$\int_0^{V_T} \frac{dV(r)}{V_T} = 1 = \int_0^{\infty} (k \lambda + k' \lambda') dr \quad (2)$$

$$= k \frac{\Gamma(\rho+1)}{\alpha^{\rho+1}} + k' \frac{\Gamma(\rho'+1)}{\alpha'^{\rho'+1}}$$

The constants  $k$  and  $k'$  can be eliminated when the following relationship is recalled.

$$V_T = V_m + V_M \quad (3)$$

so that

$$k = \frac{\alpha^{\rho+1}}{\Gamma(\rho+1)} \quad k' = \frac{\alpha'^{\rho'+1}}{\Gamma(\rho'+1)} \quad (4)$$

the final expression for the amount adsorbed per amount of carbon,  $q$ , can be written as follows:

$$q = \frac{V_m}{V_L} \frac{[1 - \Gamma(\rho+1, \epsilon)]}{\Gamma(\rho+1)} + \frac{V_M}{V_L} \frac{[1 - \Gamma(\rho'+1, \epsilon')]}{\Gamma(\rho'+1)} \quad (5a)$$

where

$$\epsilon = \alpha r \quad \epsilon' = \alpha' r \quad (5b)$$

This expression was derived with the assumption that only capillary condensation contributes to adsorption. The two terms on the right of equation 5a represent the volume adsorbed in the micropore region and the mesopore region, respectively. As in the development by Sircar, the Kelvin equation 1 must be evaluated together with equation 5 in order to complete the isotherm. As shown here, equation 5 does not reduce to a Henry's Law relationship at low vapor pressures. However, it does converge to the correct saturation limit.

Sircar did not develop the relationship for the heat of adsorption for this isotherm. This would be important if one wanted to evaluate the temperature dependence of adsorption as well the thermodynamic validity of the model. The heat of adsorption associated with the capillary condensation mechanism can be derived. The isosteric heat of adsorption is given by the Clausius-Clapeyron equation:

$$-\Delta H_s = RT^2 \left. \frac{d \ln p}{dT} \right|_N \quad (6)$$

The isotherm expression of equation 5 reveals that a constant adsorbed phase concentration implies a constant pore radius. Thus, using equation 1 the heat of adsorption can be written as:

$$-\Delta H_s = \frac{2\sigma V_L \cos\theta}{r} + \Delta H_{vap} \quad (7)$$

provided that  $\sigma$  and  $V_L$  are constant over the temperature range considered. For large pore sizes the heat of adsorption becomes the heat of vaporization while for small pore radii this expression predicts infinite heat of adsorption. This same inconsistency occurs in the calculation of the heat of adsorption with Polanyi pore filling models as the relative pressure goes to zero. In practice the first term on the right hand side of equation 7 has very little effect in the pore range considered by capillary condensation.

The modified Sircar isotherm expression in equation 5 is of interest primarily for its ability to describe capillary condensation. It presents some difficulties if it is to be used for correlating data. The large number of parameters, five, and the presence of an imbedded gamma function makes numerical calculations using this isotherm difficult.

In order to develop an expression which is more amenable for numerical calculation, a modification to the Antoine equation is proposed. Because the water isotherm is a type V, a different modification to the Antoine equation is required from that proposed by HacsKaylo and LeVan<sup>18</sup> who considered type I isotherms. The following expression is suggested to provide a correlation to water adsorption:

$$\ln p = A' - \frac{B'}{C' + T} \quad (8)$$

where

$$A' = A + (C_1 \Theta + 1) \ln(\Theta) \quad B' = B \quad C' = C + C_2(1 - \Theta) \quad (9)$$

and

$$\Theta = \frac{q}{q_{\text{sat}}} \quad (10)$$

This expression contains three adjustable parameters ( $q_{\text{sat}}, C_1, C_2$ ). The heat of adsorption can be shown<sup>22</sup> to be

$$-\Delta H_s = RT^2 \frac{B'}{(C' + T)^2} \quad (11)$$

This equation has a correct Henry's Law region because as  $\Theta$  goes to zero the isotherm becomes

$$\ln p = \ln \Theta - \ln K \quad (12)$$

and as saturation is approached this equation becomes the Antoine equation. There is no assumption in this isotherm about hysteresis, therefore nothing can be inferred about the nature of hysteresis by application of this equation. This may limit the application of this expression in water adsorption correlation.

### 3. MATERIALS AND METHODS

Six different carbon samples considered to be of military interest were studied: (1) BPL, Lot #7502, an unimpregnated activated carbon; (2) ASC Whetlerite, Lot #1227, an activated carbon similar to BPL, impregnated with copper, silver, and chromium salts; (3) ASC-TEDA, Lot #85-007, an ASC carbon with an additional impregnant, triethylene diamine; (4) CWS, Lot #06266, an unimpregnated activated carbon; (5) a polymeric beaded carbon, and (6) a foreign military filter mask carbon. Samples (1-3) were manufactured by Calgon Carbon Corp., Pittsburgh, PA. Sample (5) was a commercially prepared proprietary material.

A schematic diagram of the experimental apparatus is presented in figure 1. The house air supply is passed through a separator and dried by a molecular sieve adsorbent. Low humidity air is obtained by reducing the flow through the water bath and increasing the flow through the bypass line. Higher humidities are obtained by increasing the voltage to a heating element in the water bath and reducing the flow to the bypass line. The feedback controller of an EGG 911 Digital Humidity Analyzer activates the heating element when the sensor reading drops below the setpoint. Both the carbon samples and the reference thermocouple from the EGG 911 were placed in the constant temperature chamber.

The samples are dried for at least two days at 110 °C. The weight of carbon used in each run is between 0.4 - 1.0 g. The carbon is loaded into plastic tubes and packed with glass wool. The weight of the plastic tube and glass wool is approximately 3.0 g. Humidified air is drawn over the carbon samples using a vacuum line attached to each tube. The constant temperature chamber is used to equilibrate the feed air and carbon. The weight pickup of the samples is monitored until no change is recorded. Equilibration times are on the order of one hour. Both adsorption and desorption data can be obtained with the setup. Six carbon samples are equilibrated simultaneously in this unit.

#### 4. RESULTS AND DISCUSSION

##### 4.1 Experimental Water Isotherms

Measured equilibrium data for the adsorption and desorption of water vapor on the six carbon samples for temperatures of 15, 25, 35 °C are shown in figures 2-7. Under ambient conditions only 60% relative humidity (RH) feed air could be obtained at 35 °C. The fluid phase concentration of water vapor is plotted as percent relative humidity in order to be able to compare the adsorption at different temperatures.

The isotherms for BPL carbon, figure 2, are characteristic of water adsorption on activated carbons. It reveals that there is no significant adsorption below 20% RH but a large increase in adsorption between 20% and 80% RH. The desorption side of the water isotherm maintains a high water loading down to 45% RH where the loading drops off dramatically. This process, hysteresis, is characteristic of water adsorption on activated carbons. An important implication of hysteresis is that once the carbon is saturated with water it would take prolonged exposure to air with a relative humidity below 40% to desorb a substantial amount of water. The lower closure point of the BPL carbon occurs at approximately 20% RH. There are only slight differences between the equilibria data for CWS carbon as shown in figure 5 compared to that of BPL. There is a higher capacity of CWS

carbon for adsorbed water 0.45 g/g than for BPL 0.39 g/g. The hysteresis loop of CWS is also smaller than that of BPL.

The impregnated carbons, ASC and ASC-TEDA, display a slightly different behavior from that of the unimpregnated carbons, as seen in figures 3 and 4. The lower closure point of the impregnated carbons is never reached, which suggests that the additional amount of water retained on the ASC at low relative humidities has reacted with the impregnants. This process is reversed when the ASC carbon is subjected to higher temperatures and the weight of the samples return to their original value.

The water isotherm of the polymeric beaded carbon, figure 6, shows a very steep rise for both the adsorption and desorption curves. In addition, there is very little water adsorbed outside a narrow range of relative humidities. This material is manufactured in order to give a narrow pore size distribution in the range of 1.0 - 1.5 nm in diameter.

The foreign carbon sample had a water isotherm shown in figure 7. The prior exposure history of this sample was not known. The sample was in pelletized form as opposed to the other activated carbons studied here which were granular. The total capacity of this sample is much lower than ASC, and the shape of the isotherm is dramatically different. There is virtually no hysteresis loop. The presence of impregnants does not result in a significant amount of water being retained on the carbon at low humidities as was seen in ASC. This could be a result of weathering. Almost all adsorption occurs below 70% RH with total capacity of 0.25 g/g.

#### 4.2 Isotherm Model Application

The work of Juhola<sup>1</sup> indicated that by taking  $\cos(\theta)$  as 0.62 in the Kelvin equation that the desorption side of the water isotherm would predict the same values for the pore size distribution as that predicted by Barrett's method<sup>7</sup>. There have not been any reported studies of pore size distribution on BPL in the literature so it was not possible to compare the present data with nitrogen isotherm pore size distributions. For this work, it is assumed that Juhola's findings are valid so that the water isotherms provide a way of characterizing the pore distribution of activated carbons using the modified Sircar isotherm equation 5. This model requires that the parameters  $\sigma$ ,  $V_L$ , and  $T$  for the Kelvin equation and  $\rho$ ,  $\rho'$ ,  $\alpha$ , and  $\alpha'$  for the distribution function be specified. In the earlier work by Juhola, the adsorption and the desorption isotherms could be made to provide a pore volume distribution in agreement with that from nitrogen isotherms by adjusting the value of the contact angle and the molar volume. He assumed that adsorption differed

from desorption in the choice of the contact angle. In this work,  $\cos(\theta)$  is taken to be 1.0 for both adsorption and desorption. The molar volume and surface tension are taken as the pure component values. The total pore volume is taken from the isotherm loading at 100% RH and the liquid density.

When only a single pore volume distribution is used and all the pore volume is assumed to be micropore volume, then an acceptable fit to only one of the carbon samples can be found. Implementation of the bidisperse pore distribution model of equation 5 provides a much better fit to the rest of the data. Attempts to fit the isotherm using different values for  $\rho$ ,  $\alpha$ ,  $\rho'$ ,  $\alpha'$ , and  $V_m$  for adsorption and desorption were made. Several iterations were required in order to determine the parameters which fit the data. As can be seen in figure 2, the modified Sircar expression is able to represent the entire isotherm.

The pore size distribution parameters for the correlation have been listed in table 1. The isotherm described by equations 1 and 5 was fit to the BPL data in order to provide a qualitative estimate of the parameters. The micropore volume used in the isotherm for BPL was  $0.32(\text{cm}^3/\text{g})$ . The micropore radius distribution was centered at 1.9 nm for adsorption and 1.1 nm for desorption as shown in table 2. The mesopore radius distribution for adsorption and desorption was centered at 9.0 and 4.1 nm respectively. The pore heterogeneity term was defined by Sircar as  $(\rho + 1)^{-0.5}$ . The smaller the value of this term the more narrow the pore distribution. In order to fit the data in the micropore range, the desorption side had to have a smaller heterogeneity term or more narrow distribution than adsorption. Efforts to fit the desorption side of the isotherms of ASC and ASC-TEDA and the foreign carbons with the modified Sircar expression were not made because it appeared that the presence of the impregnants introduced additional adsorption phenomena which are not described by this model. Only a single distribution was used in the model equation in order to fit the beaded carbon data, figure 5. The adsorption data was centered at 17 nm and the desorption data was centered at 14 nm.

It would be expected that an amorphous material such as activated carbon would have a complex pore structure. The pore size distribution functions were calculated using the method presented by Sircar. Figures 6 and 7 indicate that the pore size distribution described by the modified Sircar expression is more complex than could be described by a single gamma distribution. The fact that there is some overlapping of the micropore and the mesopore distributions is an inconsistency in the model which indicates that the actual pore distribution may even be more complex than can be explained by two distribution functions.

The range of relative pressure over which adsorption occurs and the size of

the hysteresis loop are large for BPL while for the beaded carbon these are small. As indicated by this isotherm model, the relative pressure range over which adsorption occurs is related to the pore size distribution. This is consistent with the "ink bottle" theory, which assumes the presence of interconnected pores of various diameters. Further work would be required in order to establish the correlation between the shape of the hysteresis loop and the pore size distribution.

The relationship between the values of the pore radii predicted by the modified Sircar equation here and by the more traditional nitrogen adsorption methods depends on the choice of the parameters used in the Kelvin equation. It would be possible to choose values in the Kelvin equation which make these two methods agree. This would provide a means by which the water isotherm could be correlated to predict a pore radius distribution which is in agreement with the IUPAC definition.<sup>20</sup> As presented here, the distributions for micropores and mesopores do not conform to that standard.

The effect of temperature on the isotherms is not very great over the range measured. If the heat of adsorption followed the same temperature dependence as the heat of condensation, then the isotherms, when plotted on an RH scale, should overlay each other. This appears to be the case for water adsorption over the temperature range of 15 - 35 °C. The capillary condensation model seems to predict the correct temperature dependence in the isotherm. It can be shown using equation 8 that for water adsorption on activated carbon that the heat of adsorption is only about 2% greater at 1.0 nm radius than the heat of vaporization. This indicates that the heat of adsorption predicted by this isotherm model is reasonable.

Close inspection of the isotherms reveals that the desorption side of the BPL isotherm has a steeper slope at high relative humidities than the ASC carbons. If this region of high relative humidity represents desorption from the macropores then this implies that the water in the macropores is retained by the impregnants of the ASC carbons. Kloubek<sup>21,22</sup> presents studies which show that the impregnants for ASC are deposited in the macropores. Although drawing the connection between these two observations requires some speculation, this does point to utility of the modified Sircar isotherm with water vapor isotherms.

The modified Sircar expression requires five parameters for both the adsorption and desorption sides of the isotherm. It is shown that this model can provide a means of correlating isotherms governed by capillary condensation on adsorbents with a bimodal pore size distribution. The modified Sircar isotherm is not amenable to a least squares fit of the data based on the amount of computation required to fit the parameters. The isotherm is also limited by the fact, the

adsorbed phase properties and the contact angle are generally not known. The utility of water isotherms on carbons and the modified Sircar isotherm is dependent on the ability to relate the pore size distribution to performance.

Application of the Antoine type isotherm, equation 8, to correlate water vapor adsorption data resulted in the parameters shown in table 3. This correlation was performed using a nonlinear least squares fit for the constants C1 and C2. Only the adsorption data for the BPL, ASC, ASC-TEDA, and CWS were considered. The desorption side could not be fit with this function form because the change in slope was so great. The saturation capacity term,  $q_{sat}$ , was determined using the quantity of water adsorbed at 100% RH. It is seen, in figures 8-11, that the HacsKaylo-LeVan isotherm correlates the data over the entire concentration range. It provides a better fit than was obtained using the modified Sircar isotherm. Although nothing can be said about the physical significance of the parameters, C1 and C2, it is apparent that the magnitude of each parameter increases as the capacity of the carbon sample increases. The isotherm would be useful for any work where the adsorption isotherm was required for mathematical modelling, particularly when filter design relationships are developed. This equation might also be useful if it could be incorporated with a pore filling isotherm to model multicomponent vapor equilibria of water and organics.

A convenient summary of the adsorption isotherms for BPL, ASC, and ASC-TEDA is presented in table 4. These values were obtained from the best fit to the Antoine type isotherm, equation 8. This table lists the equilibrium loading as a function of relative humidity. Table 4 provides a reference for establishing the equilibrium loading on a carbon sample. Table 4 would be valuable when it is required to verify that an activated carbon sample has equilibrated to a particular relative humidity, as in the prehumidification of samples for breakthrough studies.

## 5. CONCLUSIONS

- The effect of temperature in the range of 15-35 °C is shown to be small when the water adsorption isotherms are plotted on an RH scale.
- The isotherm data for unimpregnated activated carbons can be correlated with a modified Sircar model which accounted for capillary condensation on a bidisperse pore structure of micropores and mesopores using five parameters. The data for the beaded carbon can be fit with a single micropore distribution function. These findings were consistent with the known structure of these materials.

- The size of the hysteresis loop is greater for the activated carbon than for the beaded carbon. This suggests that the presence of hysteresis for water adsorption isotherms is related to the nonuniformity of the pore size distribution of the carbon sample.
- A second isotherm correlation is proposed, based on a modified Antoine equation. The resulting equation is useful in correlating adsorption data using two parameters and the saturation capacity.
- The shape of the water adsorption isotherms of the impregnated carbons ASC and ASC-TEDA is consistent with earlier findings that the impregnants are located in the macropores.

Table 1.  
Isotherm Parameters

Bidisperse Pore Model

---

	$\rho$	$\alpha$ (nm) <sup>-1</sup>	$\rho'$	$\alpha'$ (nm) <sup>-1</sup>	$V_m$ (cm <sup>3</sup> /g)	$V_T$ (cm <sup>3</sup> /g)
BPL Adsorption	3.5	2.3	3.5	0.5	0.32	0.39
BPL Desorption	13.8	13.0	3.5	1.1	0.32	0.39
CWS Adsorption	6.0	4.6	1.0	0.4	0.32	0.46
CWS Desorption	8.0	8.0	1.0	0.4	0.37	0.46
ASC Adsorption	3.5	2.3	2.5	0.5	0.3	0.36
ASC-TEDA Adsorption	3.5	2.3	2.5	0.4	0.29	0.35
Foreign Carbon Adsorption	3.5	3.8	1.2	0.4	0.2	0.25

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Isotherm Parameters Beaded Carbon

Single Pore Distribution Model

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	$\rho$	$\alpha'$ (nm) <sup>-1</sup>	$V_T$ (cm <sup>3</sup> /g)
Adsorption	15	9.2	0.49
Desorption	19	14.8	0.49

---

Table 2.  
**Pore Distribution Parameters**  
**For Bidisperse Pore Model**

	Mean Radius (nm)		Pore Heterogeneity Term	
	Micropore	Mesopore	Micropore	Mesopore
BPL Adsorption	1.9	9.0	0.47	0.47
BPL Desorption	1.1	4.1	0.26	0.47
CWS Adsorption	1.52	5.0	0.38	0.71
CWS Desorption	1.12	5.0	0.33	0.71
ASC Adsorption	1.96	7.0	0.47	0.54
ASC-TEDA Adsorption	1.96	8.7	0.47	0.54
Foreign Carbon Adsorption	1.18	5.5	0.47	0.67

**Pore Distribution Parameters**  
**For Model of Polymeric Beaded Carbon**

	Mean Radius (nm)	Pore Heterogeneity Term
Adsorption	1.7	0.25
Desorption	1.4	0.22

Table 3.

Modified Antoine Model  
Parameters

(Antoine Parameters for  $p_{\text{sat}}$  Torr)

	C1	C2(K)	$V_T(\text{cm}^3/\text{g})$
BPL	2.56	37.9	0.39
ASC	2.32	33.3	0.36
ASC-TEDA	2.40	34.2	0.35
CWS	3.67	45.7	0.46

Table 4.

Equilibrium Loading Of Water  
On Activated Carbons  
(Temperature Range 15-35 °C)

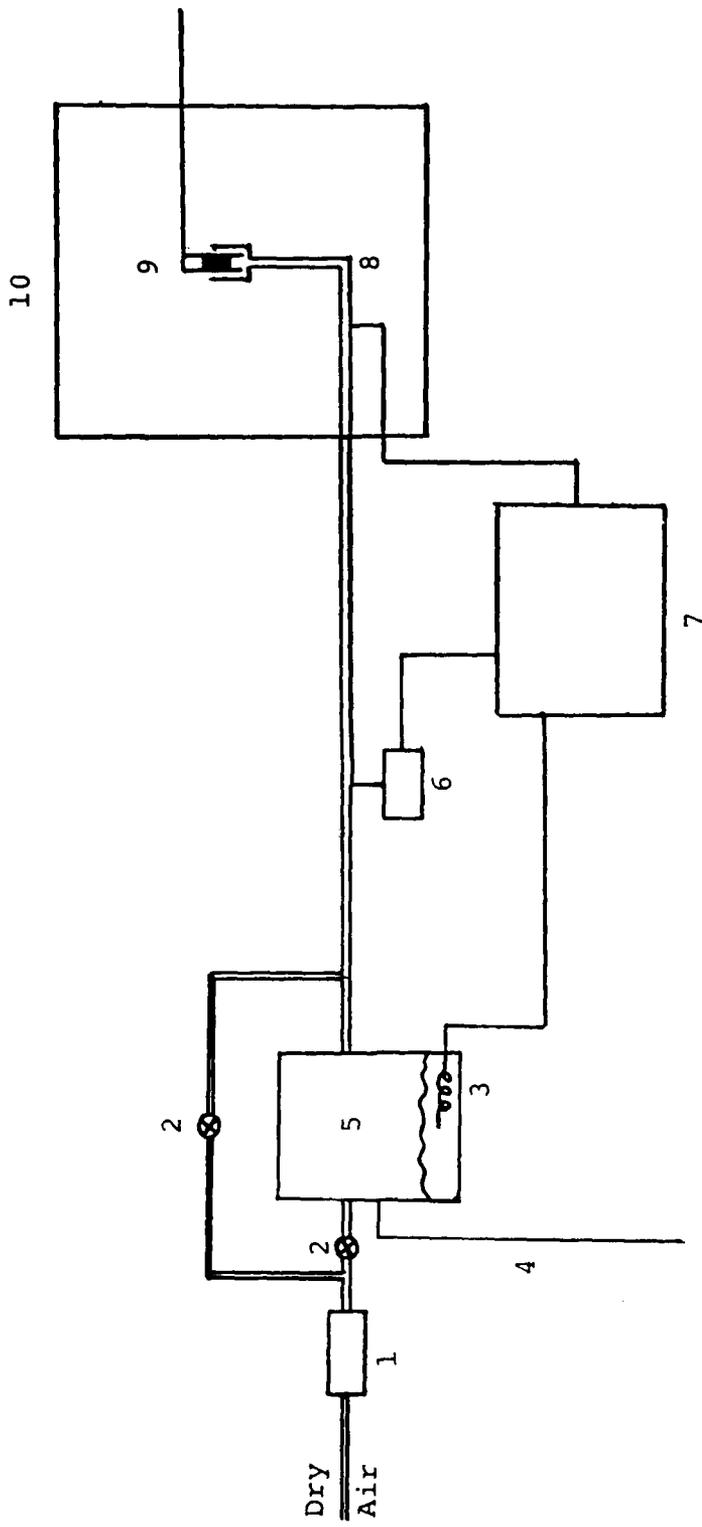
Loading (g/g)	BPL	ASC	ASC-TEDA
	(Relative Humidity %)		
0.005	7.89	6.95	7.39
0.010	13.99	12.39	13.09
0.015	18.94	16.85	17.71
0.020	23.05	20.59	21.54
0.025	26.51	23.77	24.79
0.030	29.46	26.53	27.56
0.035	32.01	28.93	29.96
0.040	34.22	31.04	32.07
0.045	36.15	32.92	33.92
0.050	37.86	34.61	35.58
0.055	39.39	36.13	37.06
0.060	40.75	37.51	38.41
0.065	41.98	38.78	39.64
0.070	43.10	39.95	40.77
0.075	44.12	41.04	41.81
0.080	45.06	42.05	42.79
0.085	45.92	43.01	43.71
0.090	46.73	43.91	44.58
0.095	47.50	44.77	45.41
0.100	48.21	45.60	46.20
0.105	48.90	46.39	46.97
0.110	49.55	47.16	47.72
0.115	50.18	47.91	48.45
0.120	50.79	48.65	49.16
0.125	51.38	49.37	49.87
0.130	51.96	50.09	50.57
0.135	52.53	50.80	51.27
0.140	53.10	51.50	51.97
0.145	53.66	52.20	52.67
0.150	54.22	52.91	53.38
0.155	54.78	53.62	54.09
0.160	55.34	54.33	54.81
0.165	55.90	55.05	55.54
0.170	56.47	55.78	56.28

TABLE 4(cont.)

Loading (g/g)	BPL	ASC	ASC-TEDA
	(Relative Humidity %)		
0.175	57.05	56.52	57.03
0.180	57.63	57.27	57.80
0.185	58.23	58.03	58.58
0.190	58.83	58.81	59.38
0.195	59.44	59.60	60.19
0.200	60.07	60.40	61.03
0.205	60.71	61.22	61.88
0.210	61.36	62.06	62.76
0.215	62.03	62.92	63.66
0.220	62.71	63.79	64.58
0.225	63.41	64.69	65.53
0.230	64.13	65.61	66.50
0.235	64.86	66.55	67.50
0.240	65.61	67.51	68.52
0.245	66.38	68.50	69.57
0.250	67.17	69.52	70.65
0.255	67.98	70.55	71.76
0.260	68.82	71.62	72.91
0.265	69.67	72.72	74.08
0.270	70.54	73.84	75.29
0.275	71.44	74.99	76.53
0.280	72.36	76.17	77.80
0.285	73.31	77.38	79.12
0.290	74.28	78.63	80.47
0.295	75.27	79.90	81.85
0.300	76.30	81.22	83.28
0.305	77.35	82.57	84.75
0.310	78.42	83.95	86.26
0.315	79.53	85.37	87.81
0.320	80.66	86.83	89.41
0.325	81.83	88.32	91.05
0.330	83.02	89.86	92.74
0.335	84.25	91.44	94.48
0.340	85.50	93.06	96.27
0.345	86.79	94.73	98.11
0.350	88.11	96.44	100.0
0.355	89.47	98.20	*
0.360	90.86	100.0	*

TABLE 4(cont.)

Loading (g/g)	BPL	ASC	ASC-TEDA
	(Relative Humidity %)		
0.365	92.29	*	*
0.370	93.76	*	*
0.375	95.26	*	*
0.380	96.80	*	*
0.385	98.38	*	*
0.390	100.0	*	*



- 1. Mass Flow Controller
- 2. Bypass Valve
- 3. Heating Coil
- 4. Water Makeup Humidity Chamber
- 5. Humidity Chamber
- 6. Humidity Sensor
- 7. Humidity Controller
- 8. Thermocouple
- 9. Carbon Bed Temperature Chamber
- 10. Thermocouple

Apparatus

FIGURE 1.

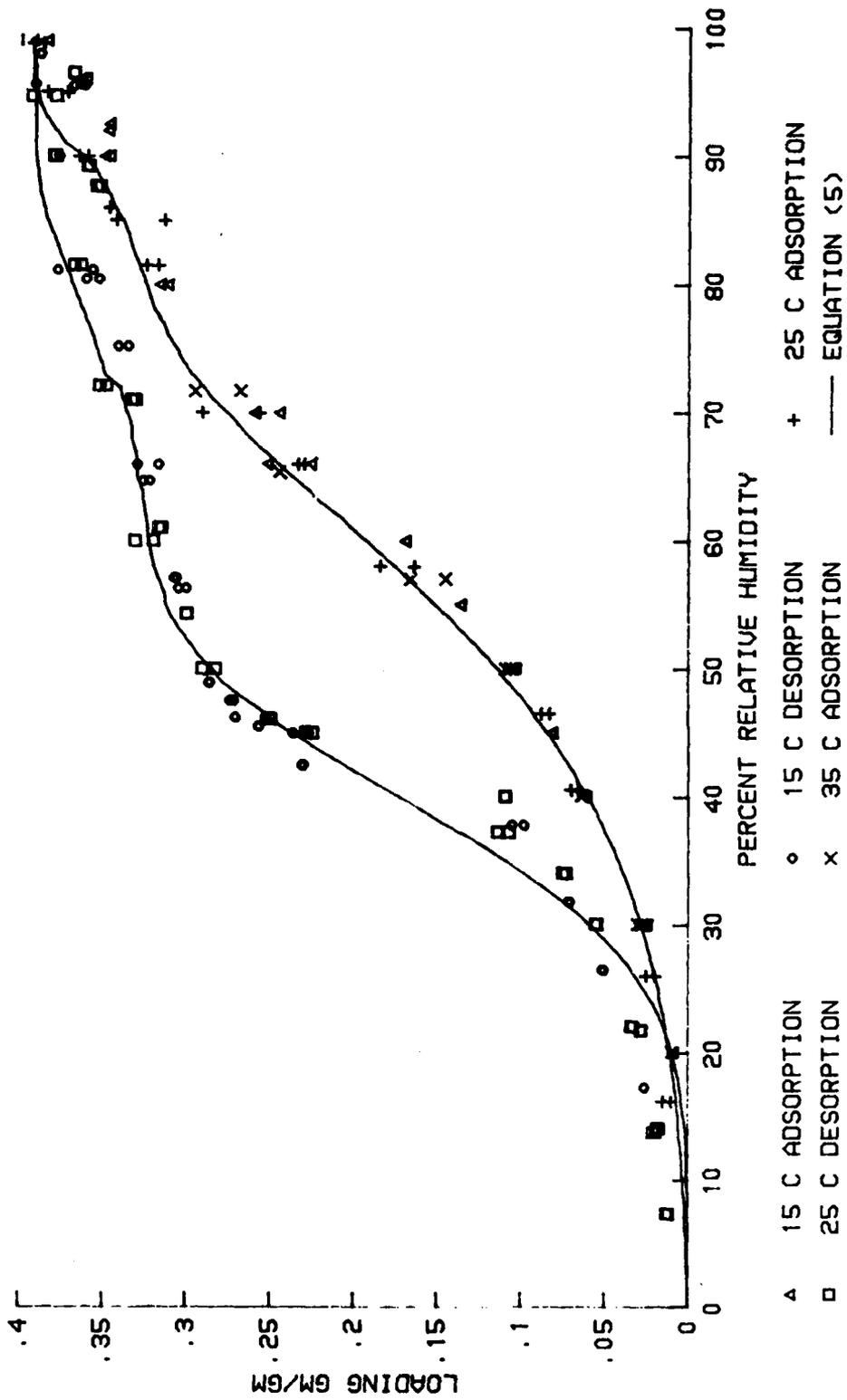


FIGURE 2.  
BPL Isotherms  
With Modified Sircar Model

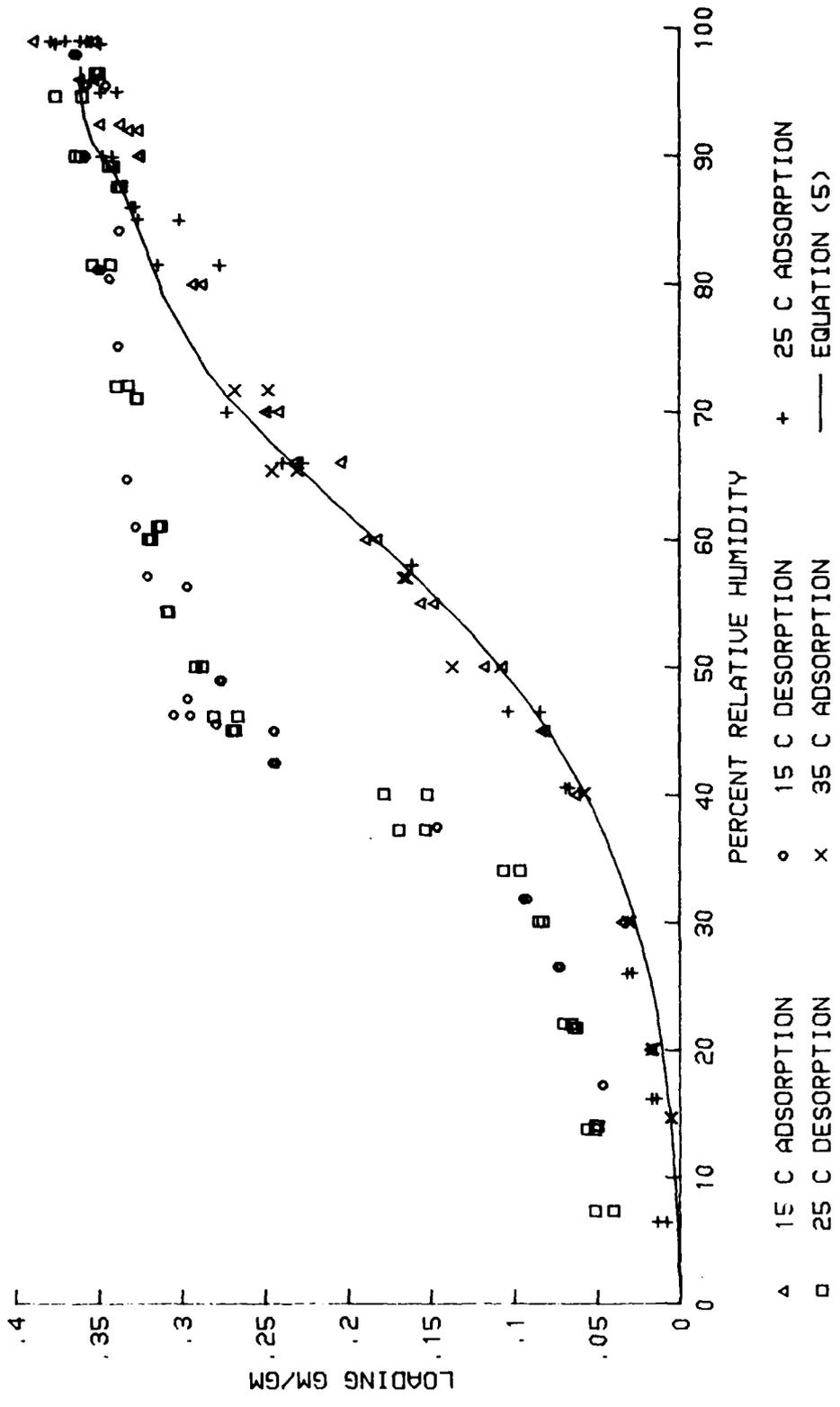


FIGURE 3. ASC Isotherms With Modified Sircar Model

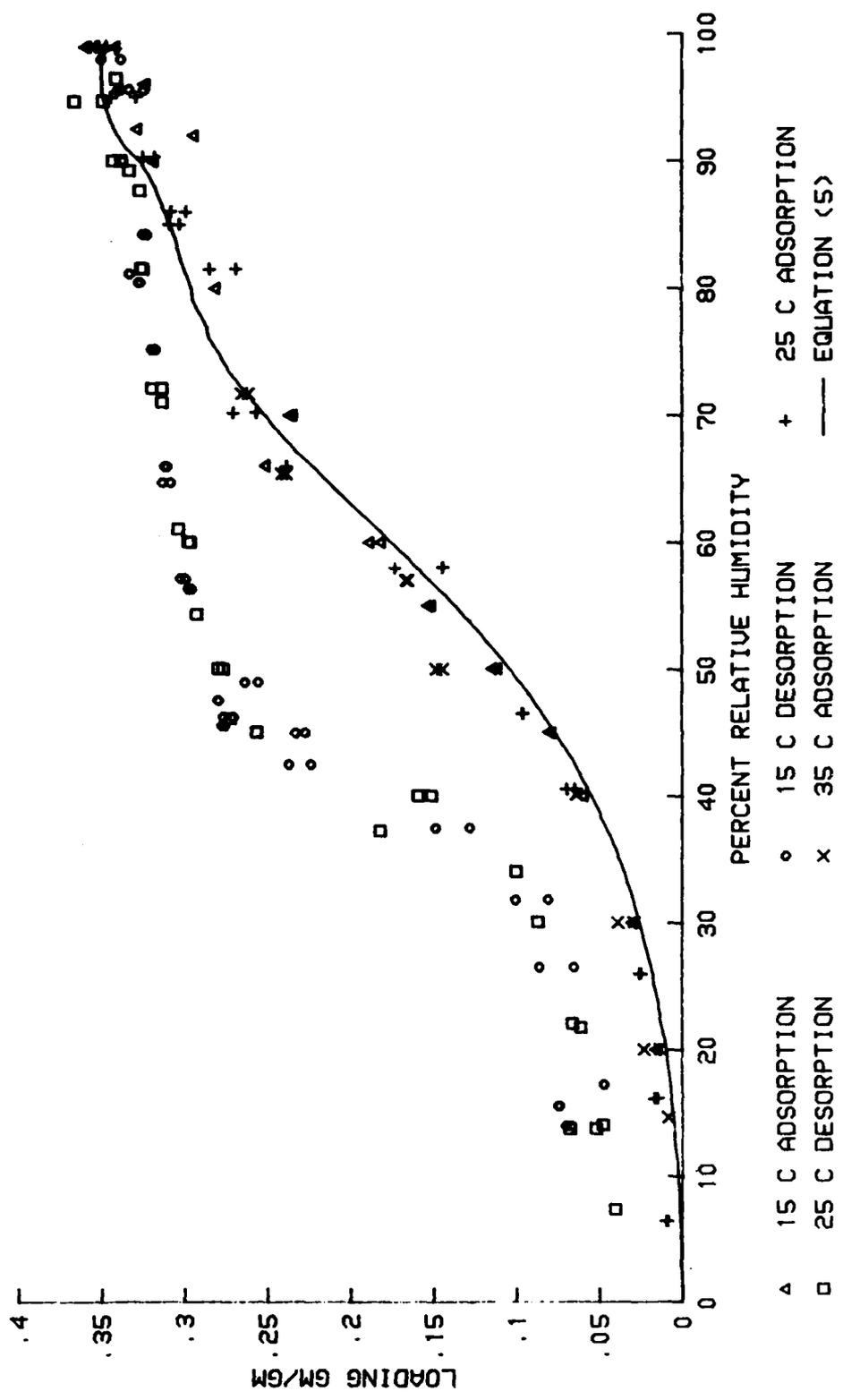


FIGURE 4. ASC-TEDA Isotherms With Modified Sircar Model

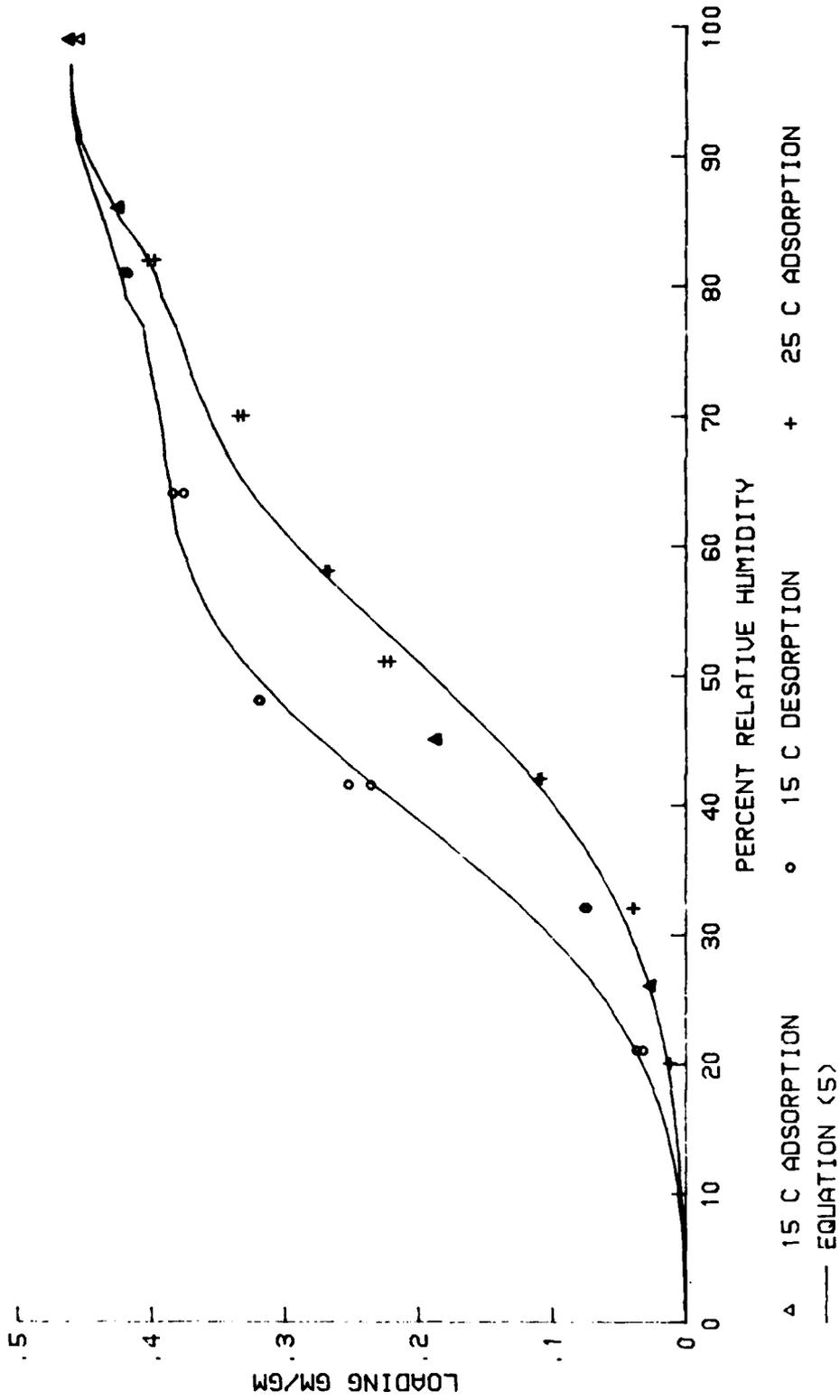


FIGURE 5.  
CWS Isotherms  
With Modified Sincarc Model

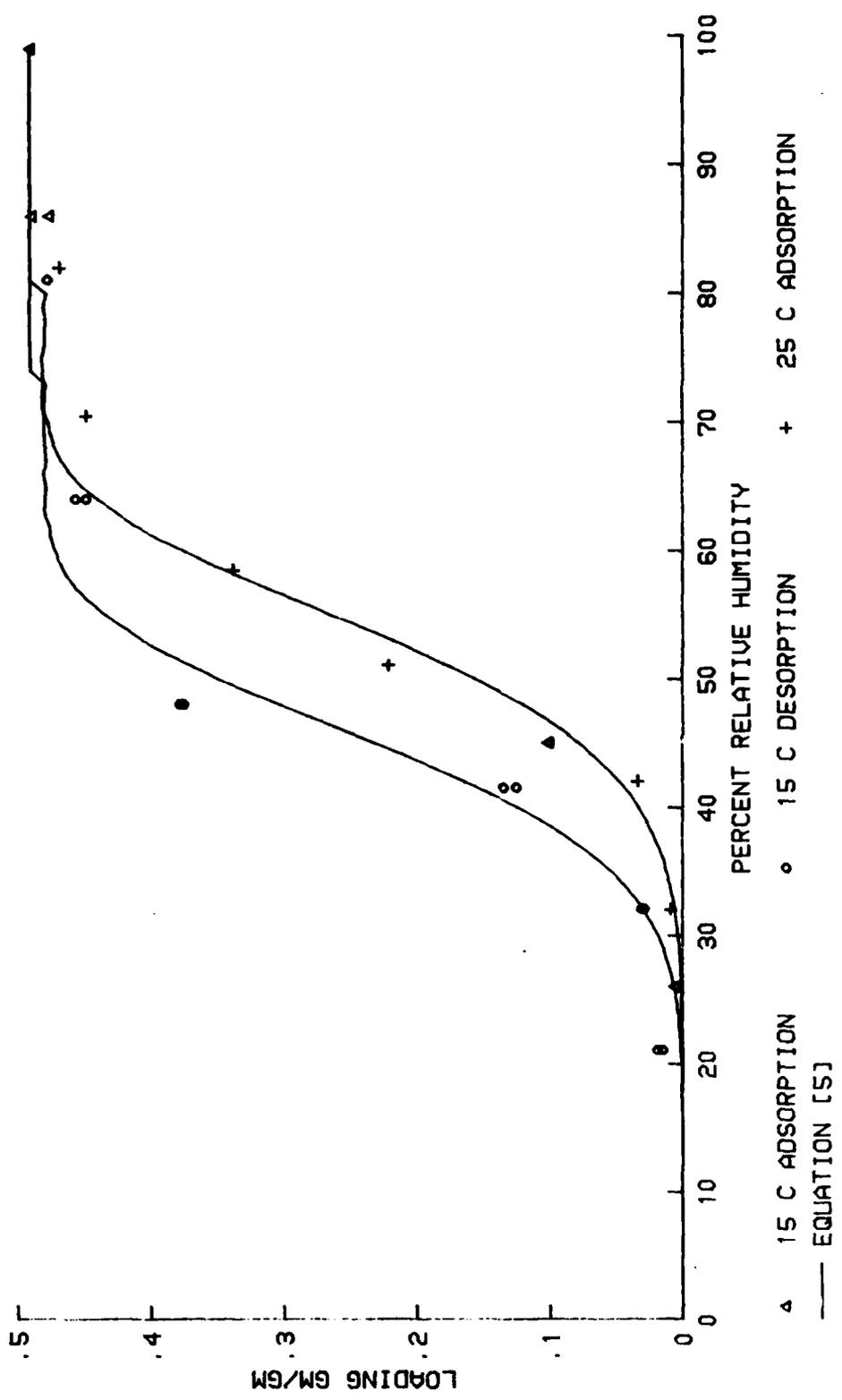
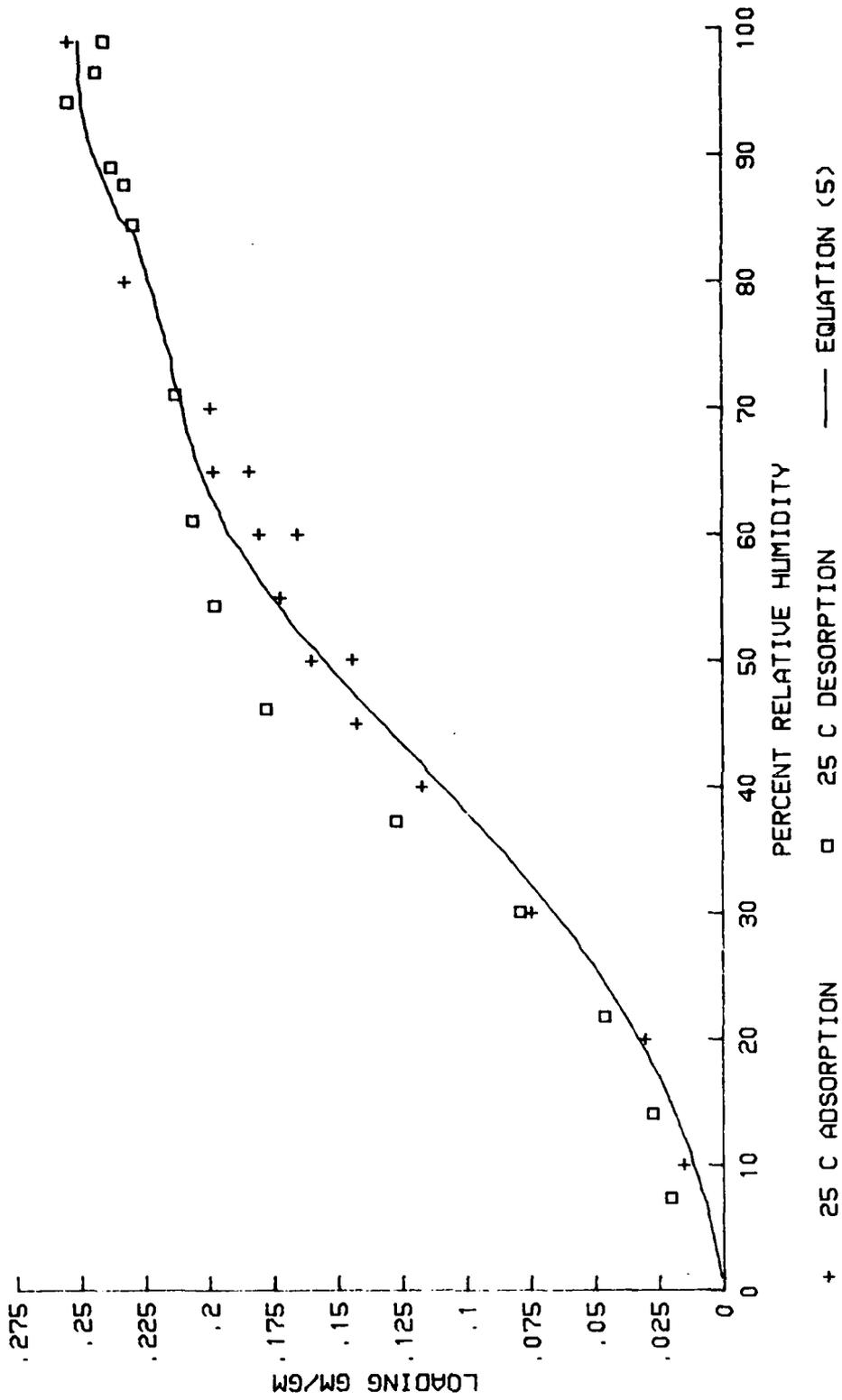


FIGURE 6. Polymeric Beaded Carbon Isotherms With Modified Sircar Model



Foreign Carbon Isotherm  
With Modified Sincar Model

FIGURE 7.

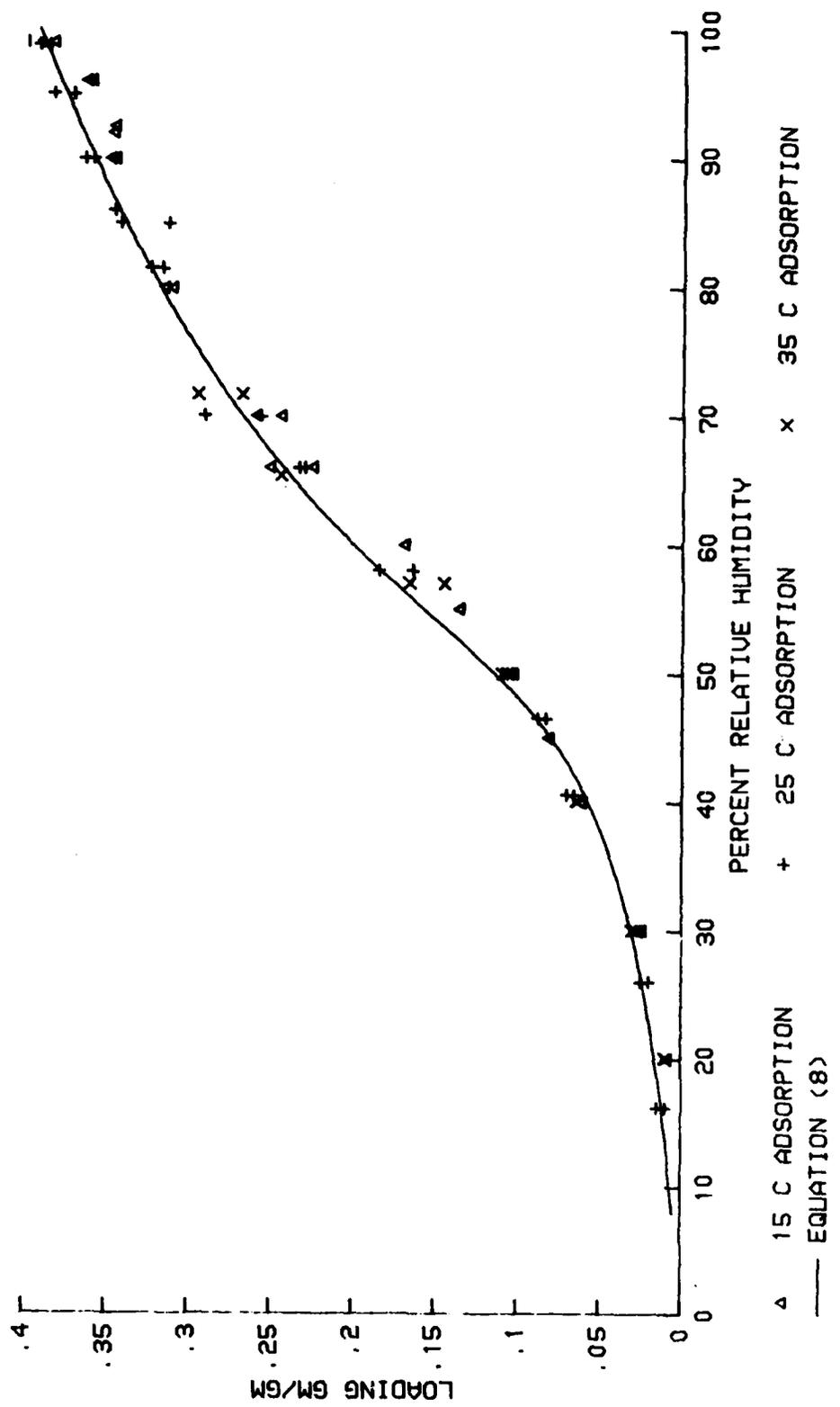
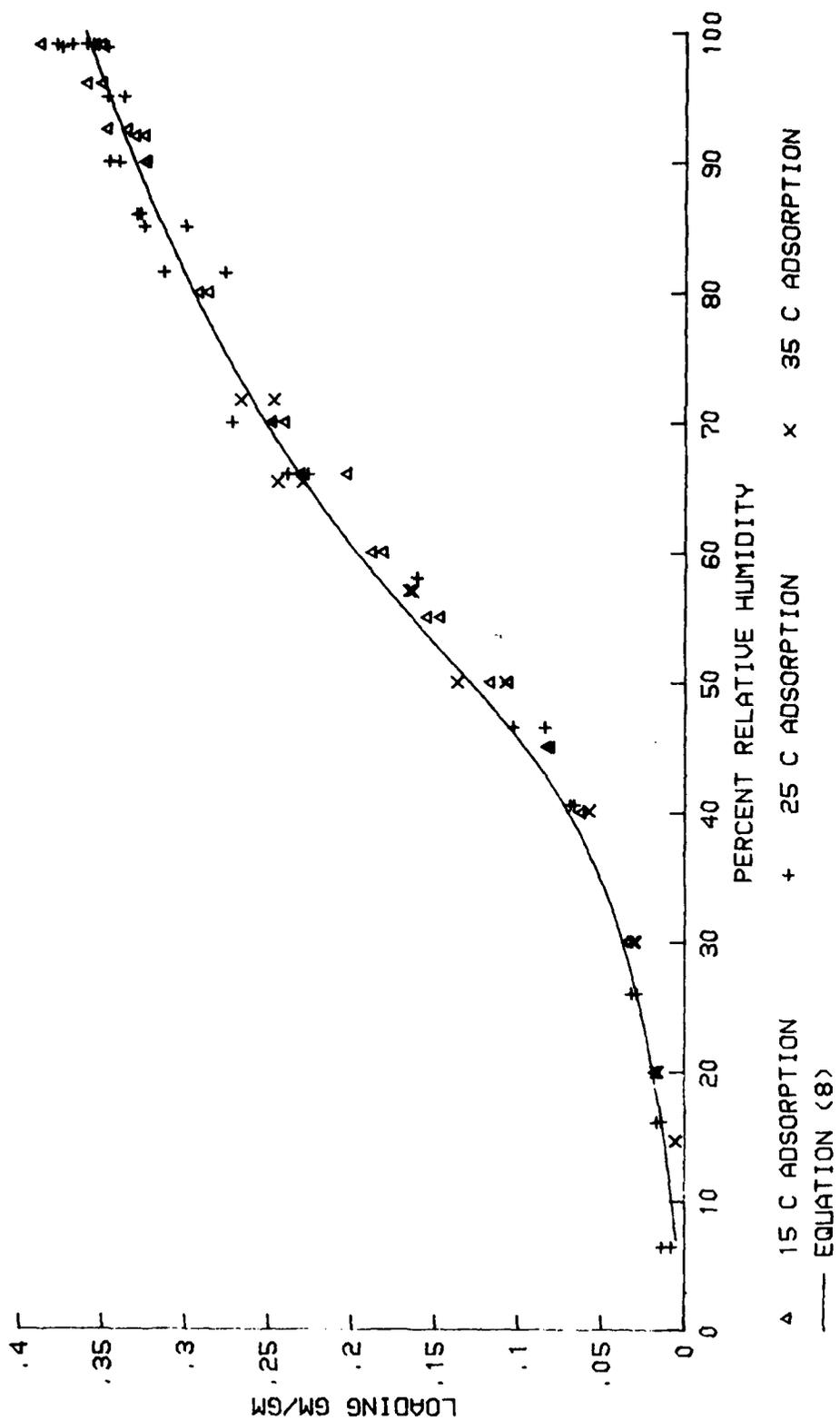


FIGURE 8. BPL Adsorption Isotherms With Modified Antoine Model



ASC Adsorption Isotherms  
With Modified Antoine Model

FIGURE 9.

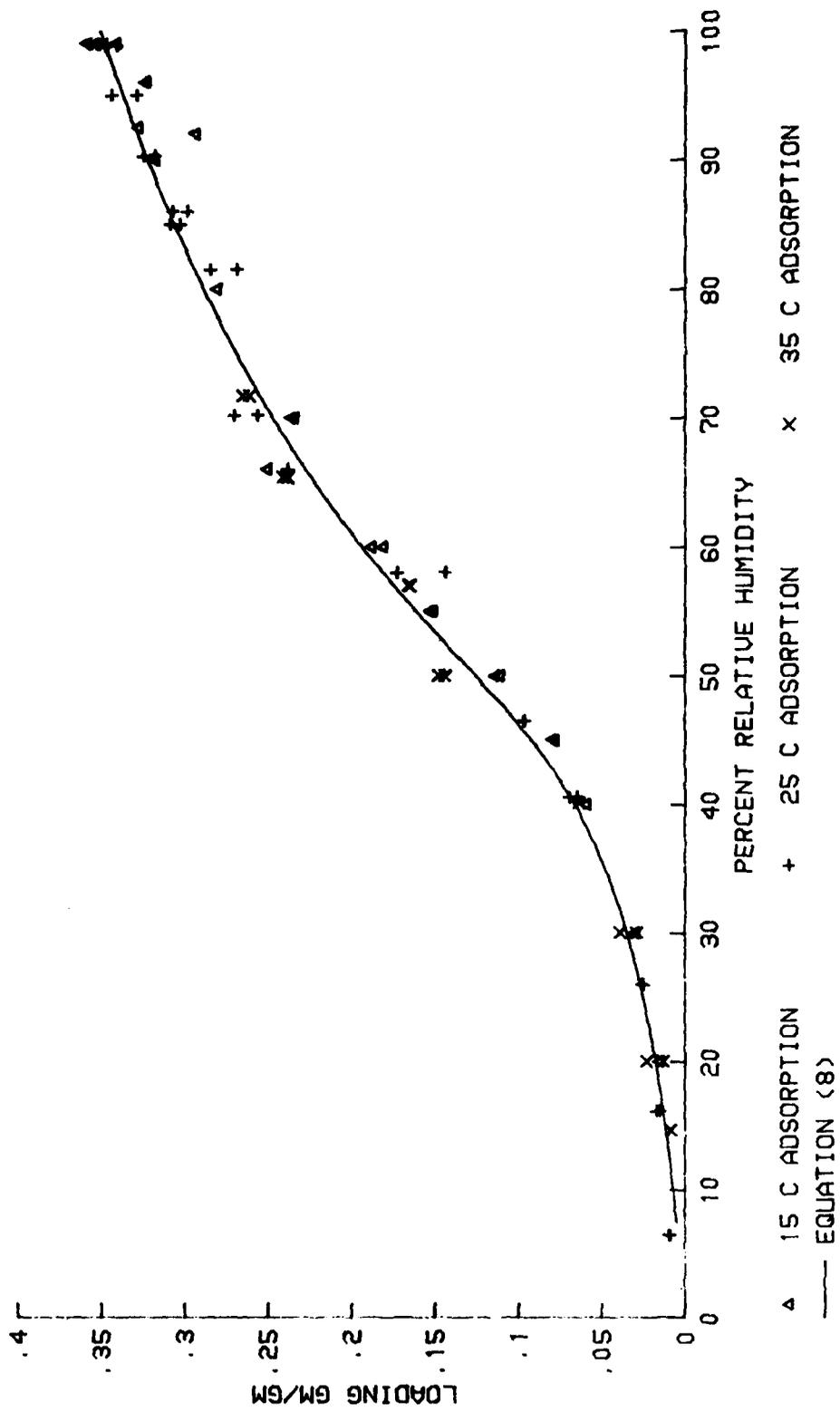


FIGURE 10. ASC-TEDA Adsorption Isotherms With Modified Antoine Model

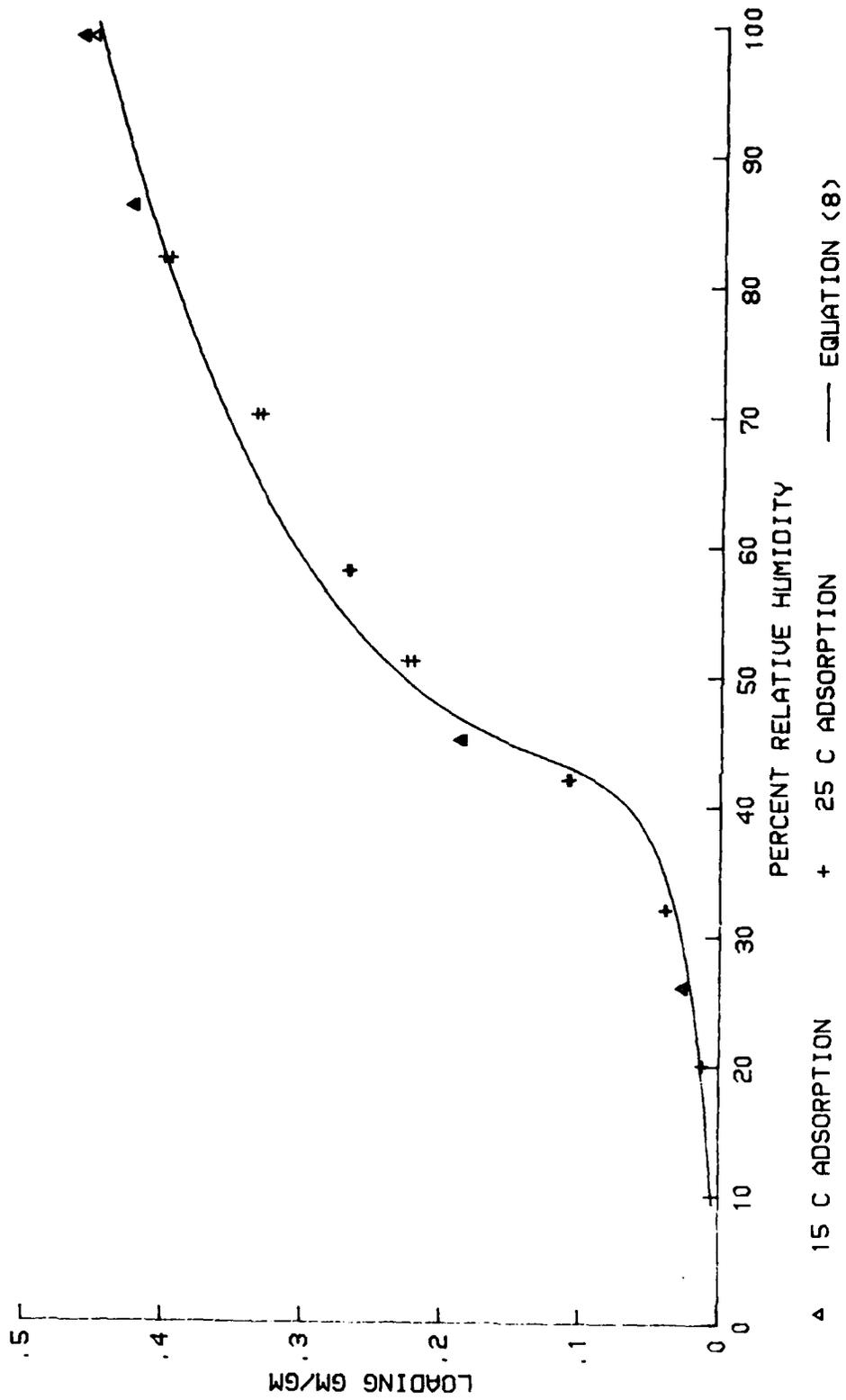


FIGURE 11.  
CWS Adsorption Isotherms  
With Modified Antoine Model

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