OXYGEN TRANSPORT IN 80/20 NYLON 6/(6I/6T), BLEND AT VARIOUS HUMIDITY VALUES

By

Nat Pinitpongskul

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

School of Packaging

1994

ABSTRACT

OXYGEN TRANSPORT IN 80/20 NYLON 6/(6I/6T), BLEND AT VARIOUS HUMIDITY VARIOUS

By

Nat Pinitpongskul

In general, the physical and barrier properties of polyamides are affected by the presence of water molecules within the polymer matrix. However, the effect of sorbed water on these properties can show different relationship such as the case of the totally amorphous Nylon 6I/6T and semicrystallline Nylon-6. In this study, the blend of Nylon-6 and Nylon 6I/6T (80:20) was carried out to improve the barrier properties of Nylon-6. Sorption equilibrium isotherm and oxygen transport characteristics of the blend were studied as a function of water activity at 23°C. Data on the water sorption isotherm and oxygen transport on the blend at 23°C are presented. Permeability (P), solubility (S), and diffusion coefficient (D) have been determined as function of water activity for both mechanisms. The P, S, and D comparison of Nylon-6, Nylon 6I/6T, and the blend has been made. The differential scanning calorimetry method was used to determine crystallinity of the blend and to investigate the effect of water on the glass transition temperature of the blend. The effect of adding Nylon 6I/6T into Nylon-6 was found to exhibit strong interactive effects on oxygen barrier improvement.

To my parents and family

ACKNOWLEDGMENTS

I would like to firstly a great deal of thanks and respect to Dr. Ruben Hernandez for his great guidance, support, encouragement and patience while serving as my major advisor.

I would like also to express my appreciation to Dr. Susan Selke and Dr. Jame P. Lucas for serving on my committees and for their useful guidance and assistance.

I am very grateful to Rafael Gavara for training, guiding, and teaching me how to operate the laboratory instrument and to solve some problems.

I would like to thank Brain Ericson for teaching me to operate Differential Scanning Calorimeter over Composite Materials and Structures Center.

I want also to knowledge the support recommend from MSU Research Excellence Project Funding.

Next, I would like to thanks Takashi Urata for his kindness to let me take his time on Cahn Instrument. Also, I would like to express a lot of thanks to Supaporn Khuandee, Sorawit Narupiti, Natawut Nupairoj, Boonchoat Paosawatyanyong, and Chatphet Saipetch for their help and encouragement.

Finally, I would like to express thanks and respect, from my heart, to my parents and all of my family.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

INTRODUCTION

Polyamides are semi-crystalline or amorphous polymers and they are widely used in industrial and packaging applications. Polyamides are very moisture sensitive. This means that the presence of water has a significant effect on transport and mechanical properties (Ohashi, 1991). For example, nylon 6, one of the most common semicrystalline polyamides, has excellent mechanical properties, and relatively good gas barrier properties at dry conditions but decreasingly gas barrier properties at high relative humidity.

Nylon 6I/6T is an amorphous polyamide that also shows a variation of permeability and mechanical properties with changing relative humidity. But, unlikely Nylon 6 , the oxygen permeability of amorphous nylon decreases as the humidity increases (Hernandez et al, 1992). Since these two polymers have different behaviors as a function of relative humidity, it is important to know the behavior of a blend of Nylon 6 and amorphous Nylon. In principle a blended polymer can be produced in which the effect of water on gas permeability may lie between the behavior of nylon-6 and of amorphous nylon.

The goal of this research is to study the transport of oxygen , through a nylon blended film (80% Nylon 6 mixed with 20% amorphous Nylon) and to compare the results with the known behavior of each of the components respectively. Oxygen permeability, and water sorption isotherm were carried out at 23°C. An isostatic permeability method was used to measure the permeability of polymer film. The diffusion coefficient (D) of oxygen in the nylon blended film was also calculated by the method of Gavara and Hernandez (1993).

Water sorption isotherms were determined by using a CAHN electrobalance. Differential scanning calorimetry (DSC) was used in this study to determine the glass transition temperature (Tg) and percent crystallinity of Nylon blended at various relative humidities.

The objectives of this study include:

1. To determine oxygen permeability of the Nylon-6/Nylon 6I/6T (80/20) blend at varying relative humidity at 23° C. From this experiment, the diffusion (D) and solubility coefficient (S) can be obtained.

2. To determine the water sorption isotherm of the blend at 23°C.

3. To evaluate the effect of humidity on glass transition temperature of Nylon blended by DSC method.

4. To compare these results with values available for pure Nylon 6 and amorphous Nylon.

LITERATURE REVIEW

2.1 PERMEATION THEORY

The transport of a gas or vapor through polymeric films involves an activated diffusion process, in which three steps can be differentiated (Stannett and Yasuda, 1965):

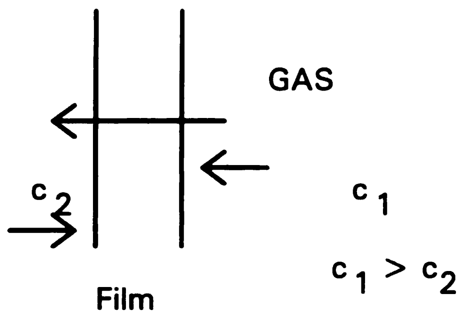


Figure 1: Schematic of gas transport through film in which c represent the concentration of the permeant within the polymer at the interface.

1) Absorption of the permeating species into the polymer matrix at the high penetrant concentration surface, c_1 indicated in figure 1.

2) Diffusion through the bulk of the polymer wall along a concentration gradient and toward the low concentration side c_2.

3) Desorption from the surface at the lower concentration.

Permeation of small molecular weight molecules through polymers is determined by the diffusion coefficient of the permeant species and the solubility coefficient of the permeant in the polymer. Diffusion of the permeant into the polymer films is driven by the concentration gradient of the permeant measured at both sides. Whereas, solubility is driven by the affinity of the permeant for the polymer (Imbalzane et al., 1991).

Under steady state conditions, a gas or vapor will diffuse through a polymer at a constant rate, if a constant pressure difference and temperature are maintained across the polymer. The diffusive flux (J) of a permeant through polymer film can be defined as the amount of permeant passing through a plane or surface of unit area normal to the direction of flow during unit time as described by equation(1).

$$J = \frac{Q}{At} \qquad (1)$$

Where Q is the total amount volume of permeant passing through area A during time t.

The relationship between the coefficient flux J and the concentration gradient is described by Fick's first law:

$$J = -D\frac{dc}{dx} \qquad (2)$$

Where:

D is the diffusion coefficient.

dc/dx is the differential inherent in concentration of the permeant across the film over a differential thickness dx.

The amount of permeant retained per unit volume of the film polymer (dJ/dx) is equal to the rate of change of concentration with time:

$$\frac{dJ}{dx} = \frac{-dc}{dt} \tag{3}$$

If Eq.(2) is substituted into Eq.(3) then:

$$\frac{dJ}{dx} = \frac{d[-D\frac{dc}{dx}]}{dx} = \frac{-dc}{dt} \tag{4}$$

and with rearrangement of the terms:

$$\frac{dc}{dt} = \frac{d[D\frac{dc}{dx}]}{dx} \tag{5}$$

and

$$\frac{dc}{dt} = D\frac{d^2c}{dx^2} \tag{6}$$

Eq. (6) is a simplified form of Fick's second law of diffusion and applies in circumstances where diffusion is limited to the cross direction of the film and D is independent of concentration (Robertson, G.L., 1992).

When the diffusion process reaches the steady state, J reaches a constant value if the concentrations c_1 and c_2 are maintained constants. Eq.(2) can then be integrated across the total thickness of the film *l*, and between the two concentrations, assuming D is constant and independent of concentration, then:

$$J = \frac{D(c_1 - c_2)}{l} \qquad (7)$$

By substituting for J using Eq. (1):

$$Q = \frac{D(c_1 - c_2)At}{l} \qquad (8)$$

When the permeant is a gas, it is easier to measure the vapor pressure (p), which is at equilibrium with the polymer, rather than the actual concentration ,c that is the concentration of permeant within the polymer. At sufficiently low concentrations, Henry's law applies and c can expressed as:

$$c = Sp \qquad (9)$$

Where S is the solubility coefficient of the permeant in the polymer.

Consequently, $$Q = \frac{DS(p_1 - p_2)At}{l} \qquad (10)$$

and rearranging equation (10),

$$P = DS = \frac{Ql}{At(p_1 - p_2)} \qquad (11)$$

where P is the permeability constant.

The steady state permeation of gases through a polymer is described by the permeability coefficient (P). The permeability coefficient (P) can be determined from direct measurement of the rate of transfer of a gas through a polymer or from the relationship of $P = DS$ where D and S are separately determined (Crank and Park, 1968).

There are seven assumptions made in the above simple treatment of permeation (Robertson, 1992).

1) The diffusion is at steady state condition.

2) Diffusion takes place in one direction only.

3) The concentration-distance relationship through the polymer is linear.

4) Both D and S are independent of the penetrant concentration.

5) Temperature is constant.

6) Henry's law applies.

7) Fick's law applies.

Unlike the transport properties of non-reacting gases (e.g. oxygen and carbon dioxide), many organic liquids and vapors create non-ideal diffusion and solubility conditions (so called concentration-dependent). This behavior is due to the ability of the organic vapors to swell the polymer matrix and thus change the configuration of the polymer chains, which increases the rate of permeation (Hernandez et al., 1986). This behavior results in a concentration dependency of the permeability coefficient.

2.2 PERMEATION MECHANISM FOR GASES THROUGH POLYMERS

Permeability is the steady state of transmission of a gas or vapor through a polymer film. During a permeability process, the gas or vapor dissolves in the material on one side or surface and diffuses through to the other side or surface by a molecular mechanism known as activated diffusion.

Mass diffusional transport through polymers differs from a flow process such as Knudsen or Poiseuille flow that occurs through porous materials. The diffusion process is affected by the characteristics of the polymer, diffusant gases, the temperature and the relative humidity (Lebovitz, 1966).

Molecular diffusion can take place because polymer chains have a random kinetic agitation or heat motion. The polymer chain segments have vibrational, rotational and translational motions that continually create temporary "holes" in the polymer matrix. The creation of these holes allows penetrant molecules to move through the polymer matrix under the influence of the concentration gradient. The amplitude and motion of the polymer molecules is directly related to the temperature, chemical composition and morphology of the polymer.

The glass transition temperature (Tg) is an important factor for the mass transport of a penetrant-polymer system (Meares, 1954). The glass transition temperature marks the transition from a "glassy" polymer state to a "leathery" polymer state. This increased flexibility of the polymer is caused by the freezing of micro-brownian motion of polymer chain segments 20-50 carbon atoms in length (Boyer, 1977). This increase in polymer chain segmental mobility above the glass transition temperature corresponds with an increase in permeability and diffusion. The permeability of polymer is higher at a temperature above T_g than at a temperature below T_g.

2.3 VARIABLES AFFECTING PERMEATION

A board range of chemical and physical properties that affect permeation is as follows (Imbalzono et al., 1991):

a) Ease of condensation of permeants

Chemicals that readily condense will, therefore, permeate at higher rates.

b) Intermolecular Chain Forces of the Polymer

With higher intermolecular forces, the permeant molecules may not be able to overcome the inter-chain forces of attraction forces. As a result, as the intermolecular forces increase within the polymer, the permeability decreases.

c) Crystallinity

Higher levels of crystallinity pose a greater barrier to permeants, because the crystalline regions block molecular diffusion. Permeation takes place only in non-crystalline regions.

d) Chemical Similarity Between Permeant and Polymer

A given permeant will be more soluble in a polymer having a similar degree of polarity. This increases the solubility and permeation rate of the permeant.

e) Molecule Size

For an identical barrier layer, the smaller the permeant molecule, the faster the permeation.

2.4 PERMEABILITY MEASUREMENTS

There are various methods for measuring permeability, which differ in terms of procedure and apparatus. In general, there are two basic test methods developed, which are referred to as the isostatic and quasi-isostatic techniques (Hernandez et al, 1986).

2.4.1 Isostatic Method

A representative transmission rate profile curve for describing the transport of a permeant through a polymer membrane by an isostatic method is shown in Figure 2. From this type of experiment, diffusion coefficient (*D*) and permeability coefficient (*P*) values are obtained, and while the specific experimental arrangement may vary among investigators, the basic equations describing the permeation phenomenon are similar.

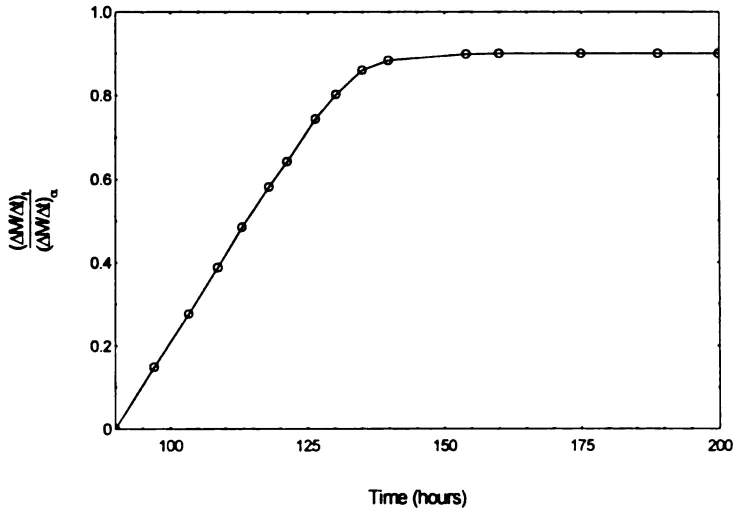


Figure 2: Transmission rate profile curve by isostatic method

A solution of Fick's first law, subject to boundary conditions of the experiment, was presented by Pasternak, et al. (1970) and is given as a first approximation in Equation (12).

$$\frac{(\frac{\Delta M}{\Delta t})_t}{(\frac{\Delta M}{\Delta t})_\infty} = (\frac{4}{\sqrt{\pi}})(\frac{l^2}{4Dt})^{1/2} \exp(\frac{-l^2}{4Dt}) \qquad (12)$$

where $(\Delta M/\Delta t)_t$ and $(\Delta M/\Delta t)_\infty$ are the transmission rates of the penetrant at time (t) and at steady state, respectively, *t* is time and *l* is the thickness of the film.

For each value of $(\Delta M/\Delta t)_t$ and $(\Delta M/\Delta t)_\infty$ a value of $l^2/4Dt$ can be calculated from equation (2). By plotting $(4Dt/l^2)$ as a function time, a straight line is obtained. From the slope of this graph, *D* is calculated by substitution in Equation (13).

$$D = \frac{(slope)l^2}{4} \qquad (13)$$

Smith and Adams (1981) used this method to study the effect of tensile deformation on gas permeability in glassy polymers.

$$D = \frac{l^2}{7.199t_{05}} \qquad (14)$$

where $t_{0.5}$ is the time required to reach a rate of transmission

$(\Delta M/\Delta t)_t$ equal to half the steady state $(\Delta M/\Delta t)_\infty$ value.

DeLassus (1985) applied Equation (14) to calculate the diffusion coefficient of limonene vapor for different polymer films typically used for food packaging.

The permeability coefficient (P) can be determined from the isostatic method by substitution into Equation (15).

$$P = \frac{aGfl}{Ab} \qquad (15)$$

where:

a = calibration factor to convert detector response to units of mass of permeant/unit of volume[(mass/volume)/signal units]

G = response units from detector output at steady state (signal units)

f = flow rate of sweep gas conveying penetrant to detector (volume/time)

A = area of the film exposed to permeant in the permeability cell (area units)

l = film thickness (thickness units)

b = driving force given by the concentration or partial pressure gradient (pressure or concentration units)

2.4.2 Quasi-Isostatic Method

In this method, the permeated gas or vapor is accumulated and monitored as a function of time. A generalized transmission rate profile curve describing the transport of a permeant through a polymer membrane by the quasi-isostatic method is shown in Figure 2. As shown, the total quantity of penetrant transmitted through the film is plotted as a function of time.

Barrer (1939) presented a solution of Equation (5) for this specific set of experimental conditions, which allowed determination of *D*, the diffusion coefficient (Hernandez, 1986).

$$D = \frac{l^2}{6\theta} \qquad (16)$$

where: θ is the intersection of the steady-state portion of the transmission curve (see Figure 3) and is called the lag time.

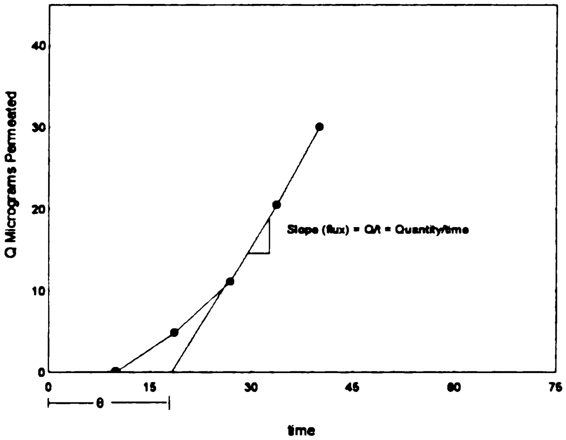


Figure 3: Generalized transmission rate profile curve obtained by quasi-isostatic method of test

The steady state permeability coefficient (*P*) can be determined from the quasi-isostatic method by substitution into Equation (17).

$$P = \frac{yl}{Ab} \qquad (17)$$

where:

y = the slope of the straight line portion of the transmission rate curve (mass/time)

l = thickness of the film

A = area of the film exposed to the permeant in the permeant in the permeability cell

b = driving force given by the concentration or partial pressure gradient

By plotting log $[t^{1/2}(\Delta M/\Delta t)_t]$ as a function of $1/t$, it is possible to obtain information about the concentration dependency of the diffusion coefficient (D) (Meares, 1965).

2.5 SORPTION MEASUREMENTS

2.5.1 Polymer Film Studies

Sorption experiments are usually carried out at equilibrium vapor pressure, using a gravimetric technique in an apparatus that records continually the gain or loss of weight by a test specimen as a function of time. A recording electrobalance (Cahn Instrument Co., Cerritos, California) is commonly used for such studies.

The diffusion equation appropriate for the sorption of penetrant by a polymer sample in sheet or film form was described by Crank (1975) as:

$$\frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2}\sum_{m=0}^{\infty}\frac{1}{(2m+1)^2}\exp\{\frac{-D(2m+1)^2\pi^2 t}{l^2}\} \quad (18)$$

where M_t is the total amount of vapor absorbed by the sheet at time t, and M_∞ the equilibrium sorption attained theoretically after infinite time; t is the time to attain M_t and l is the thickness of the film sample. The application of Eq. (18) is based on the assumption that immediately the sheet is placed in the vapor, the concentration at each

surface attains a value corresponding to the equilibrium uptake for the vapor pressure existing, and remains constant afterwards. The sheet is considered to be initially free of vapor. The value of t/l^2 for which $M_t/M_\infty = 1/2$, conveniently written $(t/l^2)_{1/2}$ is given by

$$\left(\frac{t}{l^2}\right)_{\frac{1}{2}} = -\frac{1}{\pi^2 D}\ln\left\{\frac{\pi^2}{16} - \frac{1}{9}\left(\frac{\pi^2}{16}\right)^9\right\} \qquad (19)$$

The sorption diffusion coefficient (D_s) can be calculated from Equation 18 by setting M_t/M_∞ equal to 0.5 and solving to give D_s.

$$D_s = \frac{0.049 l^2}{t_{0.5}} \qquad (20)$$

where $t_{0.5}$ is the "half-sorption time" or the time required to attain the value, $M_t/M_\infty = 0.5$.

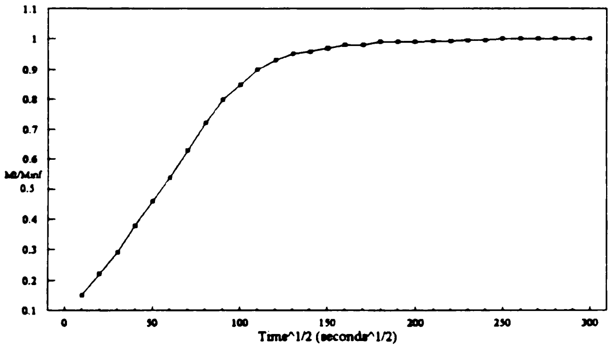


Figure 4: Typical Plot of M_t/M_∞ vs. $t^{1/2}$ for Sorption Procedure

A generalized graphical representation of Equation (19) is shown in Figure 4, where values of M_t/M_∞ are plotted as a function of the square root of time ($t^{1/2}$). Thus, the value of $t_{0.5}$ can be obtained graphically.

2.6 Sorption Isotherm Models

2.6.1 Models for polar systems at high solute activities

Solutes sorbed at temperatures below their boiling point (such as organic solvents and water at room temperature) may not obey simple, ideal phase equilibrium relations such as Henry's law. For these cases, eqn. (19) does not describe the data well over the activity range, $0<a_1<1$, and usually underpredicts the actual solubility values at high activities. This lack of agreement has been explained as a positive deviation of Henry's law caused by the swelling of the polymer network as the penetrant is sorbed. It is postulated that the network swelling exposes more binding sites and increases the sorption level of the penetrant synergistically (Vieth et al., 1976).

Berens (1975) reported that the Flory-Huggins equation adequately described data for vinyl chloride/poly(vinyl chloride) at high solute activity in the glassy state. For high molecule weight polymers, the Flory-Huggins expression is:

$$\ln a_1 = \ln V_1 + V_2 + \chi V_2^2 \qquad (21)$$

where a_1 is the solute activity, χ is the interaction parameter, V_1 is the volume fraction of the solute and V_2 is the volume fraction of the polymer. Although eqn. 21 does not provide the most accurate description of the thermodynamic performance of polymer solutions, it does contain most of the essential features which distinguish such solutions. Equation (21) usually fits equilibria data over a wider range than Henry's law and reduces to Henry's law at low gas activities.

2.6.2 Model for gas sorption in glassy polymers

The dual mode sorption model proposed by Barrer et al. is the most widely used model for analyzing the data of gas sorption. This model assumes that the solute molecules in the glassy polymer consist of non-specifically absorbed and specifically adsorbed species which are in dynamic equilibrium in the medium. Equation 22 was proposed to describe sorption in glassy polymers at high gas pressure:

$$C = C_D + C_H = k_D p + \frac{C'_H b}{1 + bp} \qquad (22)$$

Where C is the total concentration of sorbed solute in the polymer, C_D and C_H are the solubilities due to absorption (Henry's law) and adsorption (Langmuir), k_D is the Henry's law constant, b is the hole affinity constant, C'_H is the hole saturation constant and p is the pressure.

2.6.3 Modified dual mode sorption model

Hernandez et al modified eq. 21 by using the Flory-Huggins equation to describe non-specific solution in place as Henry's law. This modification should allow the model to fit over the activity range $0<a_1<1$. Other choices for the solution model are possible, but the Flory-Huggins equation is relatively simple to apply. Because the non-specific sorption term is nonlinear, the complete model can have an inflection point and should predict clustering somewhere over the range of activity values. For convenience, the modified dual mode sorption is expressed in terms of volume fractions and solute activity:

$$V_1 = V_1^{FH} + V_1^{L} \qquad (23)$$

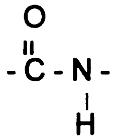
where V_1^{FH} refers to the Flory-Huggins contribution to the solute volume fraction and V_1^{L} refers to the Langmuir contribution. Since the equation (21) is nonlinear, it is convenient to determine the value for V_1^{FH} by numeric methods, such as the Newton-Raphson technique and eqn. (23) became (Ohashi, 1991):

$$V_1 = FH(a_1, \chi) + \frac{Ka_1}{1 + Ba_1} \tag{24}$$

The Langmuir equation is used to calculate the volume fraction of chemisorbed solute and the Flory-Huggins equation is used instead of Henry's law to calculate the volume fraction of water which is not chemisorbed. This model used along with a modified dual-mode sorption model represents the sorption of water vapor by an amorphous polyamide at 23°C.

2.7 POLYAMIDES

Polyamides or nylons are very important industrial polymers. Polyamides incorporate in the backbone chain of the amide function:



$$-\overset{\overset{\displaystyle O}{\|}}{C}-\underset{\underset{\displaystyle H}{|}}{N}-$$

Early development of nylons were in textile fiber applications. Polyhexamethyleneadipamide, nylon 6,6 [$-NH(CH_2)_6NHCO(CH_2)_4CO-$], the first truly synthetic fiber, was developed by W.C.Carothers synthesized in the early 1930s (Seymour, 1990). Nylons have been used commercially for packaging film applications since the late 1950s (Robertson, 1992).

Polyamides are linear condensation products characterized by repeating groups such as R_2-CONH-R_1. The various types of nylons differ by the chemical structure of segments R_1 and R_2 that separate adjacent amide groups (Turbridy and Sibilia, 1986). The first nylons were made by condensing a di-acid with a di-amine. They were characterized by the number of carbon atoms in the parent compounds.

$$H_2N(CH_2)_nNH_2 + HOOC\ (CH_2)_{m-2}COOH \longrightarrow NH\ (CH_2)_nNHCO\ (CH_2)_{m-2}CO + H_2O$$

diamine dibasic acid nylon-*nm*

$$H_2N(CH_2)_{n-1}COOH \longrightarrow NH\ (CH_2)_{n-1}CO + H_2O$$

amino nylon-*n*

Later methods were developed for the manufacture of nylons by condensation of certain amino acids which contain both the groups (-COOH and NH_2), which condense to eliminate water. These nylons are characterized by the use of a single number derived from the number of carbon atoms in the parent molecule. Thus, poly(caprolactam) based on a six carbon molecule is nylon 6 and poly(aminodecanoic acid) with eleven carbons is known as nylon 11 (Robertson, 1992). In general, they offer clarity , thermoformability, high strength and toughness over a broad temperature range, chemical resistance as well as barrier to gases, oils, fats and aromas. Biaxial orientation of nylon films is believed to improve flex-crack resistance, mechanical and barrier properties (Turbridy and Sibilia, 1986).

2.7.1 Nylon-6

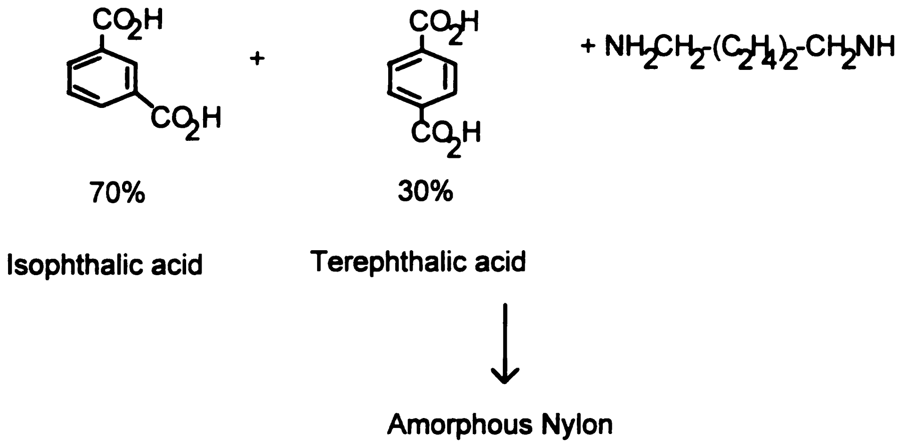
Nylon 6, which was produced by P. Schlack in 1937, is made by the anionic polymerization of ε-caprolactam (Seymour, 1990). This engineering polymer is used in the U.S. for packaging applications because of its balance of cost, physical properties and process conditions. Nylon-6 possesses high temperature, grease and oil resistance. For blown and cast extrusion, as well as cast coextrusion, nylon 6 resins are favored by most converters. When used as a component of multilayer polyolefin films, these nylons enhance properties such as barrier and high temperature sealability and yet maintain the excellent toughness of the polyolefins (Blatz, 1989).

Application

For most packaging applications, nylons are combined with other materials that add moisture barrier and heat sealability, such as LDPE, ionomer, ethylene vinyl acetate (EVA) and ethylene-acrylic acid (EAA). Nylon films have been used mostly in food packaging such as vacuum packaging, boil-in bag packs and the packaging of surgical equipment for steam sterilization (Briston, 1986 and Turbridy and Sibilia, 1986). Medical packaging applications, such as packaging of hypodermics and other medical devices, are a relatively new and expanding area for the nylons. Their toughness, puncture resistance, impact strength, abrasion resistance and temperature stability make nylons suitable for protecting sterile devices during shipping and storage. Modified-nylon resins have recently been introduced that permit radiation sterilization (Turbridy and Sibilia, 1986).

2.7.2 Amorphous Nylon (Selar® PA)

Dupont has developed a series of barrier resins under the Selar trade mark to serve the needs of the market place for all types of packaging applications. Selar® PA, a co-polymer of Hexamethylene isophthalamide and terphthalamide, is an amorphous polyamide which can be used as the barrier in both monolayer and multilayer packages for specialty chemicals, cosmetics, and certain dry foods at present, with potential for a wide variety of food applications.



Since the acid isomers are randomly placed into the polymer backbone, resulting in structural irregularity, no crystallization of the polymer matrix was observed. No evidence of crystalline melting point is found, by performing differential scanning calorimeter (DSC) analysis.

In general, properties of Nylon 6I/6T can be summarized the following;

-Nylon 6I/6T is a resin with a good combination of glass-like clarity, good barrier properties, and processing versatility. It has good mechanical and barrier properties in the presence of moisture and therefore does not have to be protected from exposure to high humidities as do other nylons.

-Second generation Selar® PA resins are under development which will have improved solvent resistance, barrier, durability, and high temperature capability.

Application

Selar® PA is being considered for a variety of packaging applications. Its glass-like clarity with its barrier makes Selar® PA considered to be a material of choice for products such as shampoo, cosmetics, household products, and dry foods replacing small glass containers. In addition, because of its properties including excellent processibility, Selar® PA is also used in packaging applications such as monolayer blow molded bottles or thermoformed containers. Developments are now underway for using the resin in flexible multilayer films for meat wrap, cereal liner and bags for snack foods. However, according to FDA regulations, the Selar® PA resin has not been approved for direct food contact. The application of Selar® PA is thus either a barrier layer or the outside layer where its glassy and transparent qualities give the containers an attractive appearance (Blatz, 1992).

2.7.3 Effect of Humidity on Nylon

Nylons are hydrophilic materials and therefore they are moisture sensitive, due to susceptible formation of hydrogen bonds with water. The absorbed moisture acts as a plasticizer in the polymer matrix. As a result, barrier and mechanical properties are noticeably affected.

Because of the presence of the hydrophilic amide group, all nylons are affected by moisture, but these effects decrease as one goes from nylon 6 to nylon 12, or nylon 6,6 to nylon 6,12 because the ratio of hydrocarbon to amide groups increases. Thus, while nylon 6 and nylon 6,6 undergo a dimensional change of about 0.65 percent at 50 percent relative humidity, nylon 11 and 12 undergo a dimensional change of about 0.10 percent under these conditions.

The volume resistivity decreases and the dielectric constant increases as the percent humidity increases, and these effects are greatest for nylon 6 and nylon 6,6 and least for nylon 11 and nylon 12. The dielectric constant at 50 percent humidity increases as follows: nylon 6, nylon 6,6, nylon 11, and nylon 12 (Seymour, 1990).

The effect of crystallinity on the equilibrium water absorption of nylons was reported by Starkweather et al.(1973). Lowering the amide group concentration and the relative humidity diminishes the effect of a change in crystallinity.

2.8 CRYSTALLINITY

Symmetrical, hydrogen-bonded, linear polyamides are invariably highly crystalline and owe their excellent mechanical behavior to this property. Yield point, tensile strength, elastic and shear module, hardness, and abrasion resistance increase with increasing crystallinity, whereas moisture absorption and impact strength drop slightly (Mark, 1969).

A number of "crystallinity" is often used as a measure of the degree of crystalline order in semicrystalline polymers. The term implies the presence of a two-phase system of crystalline and amorphous regions. This was a reasonable interpretation of the diffraction patterns of such polymers as polyethylene and polytetrafluoroethylene. Diffraction from these polymers resembles the superposition of a crystalline diffraction pattern on an amorphous pattern, which in turn appears to be an extrapolation of the diffraction pattern of the melt (Clark and Wilson, 1973). For all the nylons there is no obvious procedure for resolution of a diffraction pattern into crystalline and amorphous regions and the calculation of even an empirical degree of crystallinity. There is no obvious demarcation between crystalline and amorphous areas. An instrument such as the Du Pont 310 curve analyzer can be used to resolve these patterns but the results can be quite arbitrary. Thus for polyamides, x-ray diffraction is not commonly used to derive a measurement of crystallinity.

The usual methods for assessment of degree of crystallinity in nylons are by measurement of density or by infrared techniques. Measurement of density is perhaps most satisfactory because it is rapid, precise, and unaffected by sample orientation and geometry. It is not an absolute method, however, and requires calibration - the assumption of amorphous and crystalline densities. It also requires close control over water content. Ideally, the samples to be compared should be dry. The plasticizing effect of water on a dry sample of low crystallinity may increase its crystallinity. It should also be realized that massive samples are typically not uniform in crystallinity (Kohan, 1973).

The differential scanning calorimetry method for determining the percent crystallinity of a semicrystallinity polymer is based on the measurement of the heat of fusion, ΔH_f, and the reasonable assumption that this quantity is proportional to the percent crystallinity (Wunderlich and Cromier, 1967). The percent crystallinity may be calculated from:

$$\%Crystallinity = \frac{\Delta H_f}{\Delta H_f^{\circ}} \tag{25}$$

Where ΔH_f^* is the heat of fusion for a hypothetical 100% crystalline sample. For nylon-6, ΔH_f^* is 195 J/g (Brandrup and Immergut, 1991).

2.8.1 Effect of Crystallinity on Properties

The effect of crystallinity on the properties of nylons is substantially the same as it is for other semicrystalline polymers. Modulus and strength and related properties such as hardness and yield point increase with increasing crystallinity. Measures of toughness such as impact strength decrease, particularly in the high-crystallinity range.

However, the effect of crystallinity can hardly be discussed independent of that of water. The properties of polyamides are as dependent on water content as they are upon crystallinity. Not only can water have an effect on crystallinity, but it also changes physical properties independently. Once a sample has absorbed a given amount of water at any temperature, this water can be removed and replaced at this temperature without noticeable effect on crystallinity, but the effects on properties will be substantial. Water acts as a plasticizer for nylons and lowers the glass transition and the characteristic temperature of mechanical relaxation.

2.9 GLASS TRANSITIONS

Most polymers are either completely amorphous or have an amorphous -like component even if they are crystalline. Such materials are hard, rigid glasses below a fairly sharply defined temperature known as the glass transition temperature Tg. At temperatures above the glass transition temperature, at least at slow to moderate rates of deformation, the amorphous polymer is soft and flexible and is either an elastomer or a very viscous liquid. Mechanical properties show profound changes in the region of the glass transition. Many other physical properties change rapidly with temperature in the glass transition region. These properties include coefficients of thermal expansion, heat capacity, refractive index, mechanical damping, nuclear magnetic resonance behavior, and electrical properties. The importance of the glass transition temperature, Tg, in the mass transport of penetrant polymer systems was described by Meares (1954), and is now very well recognized.

The glass transition temperature of any amorphous substance, whether polymeric or not, is defined as the point where the thermal expansion coefficient undergoes a discontinuity. In polymers, there may more than one discontinuity in the thermal expansion coefficient. The largest discontinuity is usually associated with the loss of the molecular mobility which permits configurational rearrangements of the chain backbones.

A number of physical properties, such as thermal and electrical conductivity, optical properties, chemical luminance, fluorescence and gas permeability are affected significantly by transitions. The effect of T_g on gas permeability is of considerable practical importance since a large number of polymeric systems are used as coatings or protective materials in the form of paint or plastic film (Bear, 1964).

The sorption of gases above T_g indicates that the heat of solution must include along with the heat of interaction between the diffusant and polymer, the energy for separating the polymer chains which is endothermic, therefore accounting for the endothermic and slightly exothermic heat of solution. The exothermic heat of solution below T_g can be explained by the inclusion of the exothermic heat of adsorption for the "hole filling" in the heat of solution. The diffusion process above T_g requires a larger zone of chain activation than below T_g which is consistent with the higher surge of activation reported above T_g (Hopfenberg and Stannet, 1973).

The glass transition temperature is generally measured by experiments which correspond to a time scale of seconds or minutes. If the experiments are done more rapidly so that the time scale is shorted, the apparent Tg is raised (Nielson, 1974).

Blatz (1989) had measured the glass transition temperature of nylon-6 by using differential scanning calorimetry (DSC). However, no glass transition temperature could be determined for the nylon-6 because it is probably hidden in the crystallinity exotherm. According to Blatz, nylon-6 has a melting point (Tm) of 222°C and glass transition temperature (Tg) of 39°C. This Tg value of nylon-6 is reasonable from the relationship $T_g/T_m \sim 0.6$.

The glass transition temperature of a nylon shifts to a lower temperature as the water content is increased. The Tg of nylon-66 decreases from 80°C for an almost dry sample to 15°C for a sample saturated with water (Starkweather, 1973).

2.10 POLYMER BLENDS

Polymer blends may be defined as intimate mixtures of two kinds of polymers, with no covalent bonds between them. Historically, the oldest and simplest method involves mechanical blending, where a plastic and a noncrosslinked elastomer are blended either on open rolls or through extruders (Matsuo, 1968). Materials prepared in this manner usually contain several percent of elastomer dispersed in a plastic matrix, as shown schematically in Figure 5:

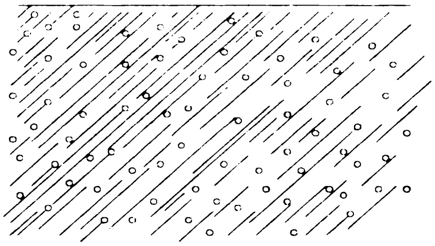


Figure 5: Schematic illustration of rubber droplets dispersed in a continuous plastic phase.

In simple mechanical blends the plastic component usually predominates, with the dispersed elastomer having dimensions of the order of several micrometers. The shear action of mechanical blending also generates free radicals through polymer degradation reactions. The free radicals thus induced by mechanochemical action subsequently react to form a small number of true chemical grafts between the two components. The quantity and importance of such grafted material obviously depend on the exact mode of blending (Casale and Porter, 1971). Significant improvements in impact resistance and toughness are usually noted for such blends over the plain parent plastic, even in cases where no particular amount of grafting is noted.

Polyblends are characterized by their phase behavior: miscible and immiscible. The miscible and immiscible are characterized by a glass transition temperature, exhibit homogeneity under magnification in an electron or phase contrast microscope and have physical properties intermediate between those of blend components.

2.10.1 Miscible and Immiscible Blends

A blend with a glass transition temperature as well as a single amorphous phase will be classified as miscible. Films of miscible blends tend to be transparent, show smooth variation of properties with composition, and have only one phase. A miscible polymer blend will exhibit a single glass transition between the T_g's of the components with the sharpness of the transition similar to that of the components. However, blends of components having similar glass transition temperatures will provide ambiguous cases and other techniques must be employed. The advantages of use of miscible blends are to overcome specific problems such as processability, heat distortion, hardness, tensile strength, creep and so on. The physical properties of these ploybleuds are generally a compromise that, on balance, may be superior to the properties of the individual constituent polymers.

Immisicibility in polymer blends is rarely well concealed, revealing itself as opacity or not opacity, delamination, double glass transition, discontinuous variation of properties with composition, having substantial morphology effects or combination of these properties because of the presence of two or more phase (Olabisi, et al. 1979, Gaicin, 1993). Blends of immiscible polymers have high interfacial tension and poor adhesion between two phases. This interfacial tension contributes to higher viscosities, difficulty in imparting desired degree of dispersion to random mixtures and to their subsequent lack of stability to phase separation during use. However, sometimes immiscibility is desirable to achieve a synergistic combination of the two polymers to form a polymer alloy.

The miscibility or immiscibility of two polymers is dictated by the thermodynamics of the mixture. The free energy of mixing ΔG_{mix} is given by

$$\Delta G_{mix} = \Delta H_{mix} - T\Delta S_{mix} \tag{26}$$

This quantity, consisting of enthalpic *(ΔG)* and entropic *(ΔS)* parts, is a function of composition and temperature *(T)*. For miscibility, ΔG_{mix} must be negative. Because of the small number of moles of each polymer in the blend, the entropy of mixing is very small and so for most of the polymer blends , the free energy of mixing is positive. Specific interactions, like hydrogen bonding, dipole-dipole interactions or intramolecular repulsion effects can also lead to some degree of miscibility. This may explain the partial miscibility among halogenated polymers and those containing oxygen (Paul, 1978).

Generally, blending technology rests on the premise of property additivity, although the additivity principle is not strictly valid for most polyblends. Although additivity is not always simple arithmetically for a quasi-binary miscible polyblend, extensive experimental data suggest that the following arithmetic semiempirical rule is obeyed by the glass transition temperature (T_g) and the other physical properties:

$$P = P_{1\Phi 1} + P_{2\Phi 2} + I_{\Phi 1\Phi 2} \tag{27}$$

Where P is the property of interest, Φ the concentration, and I is an interaction term that can be positive, negative, or zero. If I is zero, the rule of mixtures (additivity principle) is obeyed; if it is positive, the polyblend property would be better than the weighted average of the constituent polymers, and the polymers are said to be synergistic with each other. If I is negative, the polyblend property would be below what is expected from simple averaging and the system could be referred to as nonsynergistic.

2.10.2 Selecting a Polymer Combination

The reasons to combine polymers are to achieve an economic and property advantages: cost, processibility, mechanical properties, chemical resistance, thermal performance, recycling, and permeability. The strongest reason for blending polymer is the cost : performance ratio. An expensive polymer whose property spectrum is much higher than is needed for a new application may be blended with an inexpensive polymer whose property spectrum is such that the resulting polyblend has a cost : performance ratio that makes it very attractive for the given application. Thus, the standard of performance demanded by the new application is satisfied by a mixture of commercially available polymers without the need to develop a new polymer.

2.10.3 Previous Studies of Amorphous Nylon and Nylon-6 Blends

The properties of films from blends of amorphous nylon and crystalline nylons were studied by E.I. Du Pont De Nemours & Co. Inc.. The unusual mechanical properties at low humidities along with good barrier properties have been revealed.

Resins and Process used

"The type and ratio of the monomers used in the amorphous polyamide were selected such that crystallization could not occur and that the resin glass transition temperature was well above that for the crystalline nylon. The blends were prepared by extrusion blending mixtures of an amorphous copolyamide based on hexamethylenediamine and a 70/30 mixture of isophthalic and terephthalic acids (codes AMN) and an extracted polycaprolactam (nylon 6). The amorphous polyamide (AMN) has a dry glass transition temperature (Tg) of 125°C and the nylon 6 has a melting point of 222°C and a Tg of 39°C. Extrusion blends of the following AMN/6 nylon compositions were produced: 20/80, 25/75, 30/70, 35/65, 50/50, and 80/20.

The pre-melt blended resins were pelletized, dried and then extruded into film using semi-works flat die chill roll cast film equipment. As excellent contact was made between the molten web and the chill roll, the melt was rapidly quenched below the glass transition temperature. The melt temperatures used were increased from 240°C for neat nylon 6 to 275°C for the neat amorphous nylon. Correspondingly, the chill roll temperature was increased form 30°C for neat nylon 6 to 80°C for the neat amorphous nylon. Films 1 mil thick were produced with all of the blend compositions at about 50 feet/min using a 10 inch diameter chill roll. The films were placed under a dry nitrogen blanket immediately after preparation and were exposed under controlled humidity conditions before testing. It was found early in the study that exposure to humidity has a profound effect on film properties for some of the compositions."

The properties of flat die cast film from blends of amorphous nylon and nylon 6 in the composition range 30/70 to 35/63 have been measured and found to have unusual toughness properties when kept dry. However, the film toughness decreases to the expected level when the films are exposed to humidity. This phenomenon has been explained using a thermal analysis technique which is used to determine the amount of crystallinity in the films. The unusual toughness results from the low crystallinity levels and therefore greater than normal amount of amorphous polymer in blends. On exposure to moisture, the films absorb water resulting in a drop in the glass transition temperature below ambient, thereby allowing further crystallinity to occur which reduces the toughness. Films from compositions outside of this range do not exhibit unusual toughness. Lower amorphous nylon levels do not reduce the crystallinity sufficiently and higher amorphous nylon levels although having low crystallinity levels contain a higher amount of the more brittle amorphous nylon resulting in low toughness (Blatz, 1989).

MATERIALS AND METHODS

Materials

1. Polymer film

Nylon 6I/6T blended with Nylon-6 (20/80)

Film made from a blend of 20% Nylon 6I/6T and 80% Nylon-6 was provided by Allied Signal, Inc., (Morritown, NJ). Thickness of the film blend was 1.15 mils or 29.2 microns.

2. Carrier gas

2.1 High purity dry grade nitrogen gas produced by AGA Inc. (Cleveland, OH) was used throughout the studies as the carrier gas for the water vapor.

2.2 Special grade gas, hydrogen:nitrogen gas (1:99), produced by AGA Inc. (Cleveland, OH) was used in the measurement of permeability of oxygen.

3. Salt solution

Salt solutions in closed containers were used to generate selected values of relative humidity.

Methods

1. Sorption Equilibrium Isotherms

Water sorption equilibrium measurement of the polymer film were carried out on a Cahn Electrobalance Model 2000 (Cahn Instruments Inc. Cerritos, CA). A humidified stream of nitrogen adjusted to specific values of water activity provided the source of water vapor in equilibrium with the polymer films. The film samples were carefully dried under vacuum at 70°C until constant weight before starting a run. The electrobalance was maintained in a constant temperature (23 ±0.2°C) during the experiments. A sample film approximately 100 mg was normally used for equilibrium sorption data, and the sensibility of the Cahn Electrobalance was around 1 x 10^{-6} g. The test system allows for the continuous collection of sorption isotherm data for water vapor by the polyamide film from the initial time zero, when the film is first exposed to the vapor, to the steady state condition, when sorption equilibrium is reached. The Nylon film sample to be tested was suspended directed from one arm of the electrobalance and a constant concentration of penetrant or water content was continually flowed through the sample tube, such that the sample film was totally surrounded by the vapor. A constant concentration of permeant vapor was produced by bubbling nitrogen gas through distilled water. The concentration obtained in this way was adjusted to the required value by mixing it with a pure nitrogen stream. Water activities were measured using a hygrometric sensor. The vapor generator system and humidity sensor were mounted in the constant temperature chamber. The gain in weight of the sample due to penetrant sorption was monitored continually until the gain was zero at equilibrium.

2. Oxygen Permeability

Oxygen permeability studies were performed using a continuous flow system, employing the Ox-Tran 100 Permeability Tester (Modern Controls, Inc., Elk River, MN). This apparatus was modified to allow the two streams, oxygen and carrier gas, to be adjusted to specific water vapor activities. Each stream was formed by mixing a wet and dry gas component to obtain the required activity value. Activities were measured using hygrometer sensors. Sample films were also dried under vacuum at 70°C.

3. Differential Scanning Calorimetry

The Differential Scanning Calorimetry (DSC) experiments were performed on a Dupont 2200 Thermal Analyzer (Research Center at Michigan State University). Film samples were placed in small aluminum pans and vacuum dried at 70°C. Sample were then equilibrated over salt solutions to give selected water vapor activities at room temperature.

The differential scanning calorimeter was programmed at a heating rate of 10°C/minute and the heating temperature range of room temperature to 300°C, with approximately 5-10 mg of sample film in each run.

EXPERIMENTAL ERROR

PERMEATION

1. Thickness of the film

The thickness of the film was measured with an error of ±20%.

2. Experimental error in the permeability apparatus

The MoCon OX-TRAN 100 permeability tester was calibrated with a standard material (PET), 1470 Polyester film from the US Department of Commerce, National Institute of Standard and Technology. The sensor in the Oxtran 100 should be protected from oxygen in the air. Brief exposure to high concentrations will not damage the cell, but will disable it and require a recovery period of several hours before a acceptable base line is obtained. The sensor Hygrodynamics® from New Part Scientific Inc. was used to measure relative humidity during each run with a sensitivity error of 2 to 4%.

3. Temperature

Since the permeability process is temperature dependent, the temperature was precisely controlled to avoid error within 1°C.

SORPTION

1. Sensitivity of electro-balance

The sensitivity of the electro-balance can be estimated at 10 micro grams, since it is placed in a special chamber and protected from potential vibrations. External vibration transmitted to the electrobalance can cause unwanted errors.

2. Gas flow regulator

The flow regulators used must be accurate and precise to generate an identical flow rate during the test and between replicate runs. In addition, the nitrogen gas used to generate proper vapor concentration has to be checked to maintain a constant pressure throughout the experiment.

RESULTS AND DISCUSSION

1. SORPTION ISOTHERM

1.1 Equilibrium Sorption Isotherm

Water sorption isotherms were determined to characterize the sorption capacity of the blend. The sorption also is needed to relate the change in oxygen solubility to the presence of water. Water sorption isotherms were determined at 23°C. Sorption equilibrium values of water in the amorphous nylon/nylon-6 (20:80) are presented in Table 1.

Table 1: The relationship between relative humidity and weight fraction

Relative Humidity	Weight Fraction
3	0.0029
6	0.0043
13	0.0123
48	0.0364
55	0.0428
58	0.0449
67	0.0526
75	0.0603
85	0.0793

Figure 6 shows the plot of the experimental sorption values and Langmuir-Flory-Huggins values. The Langmuir-Flory-Huggins values were obtained by using a computer program prepared by Dr. R.J. Hernandez. A Flory-Huggins/Langmuir model was chosen for data description because this isotherm can be easily correlated with the adsorption (Langmuir) and absorption (Flory-Huggins) contribution.

Figure 7 shows the plot of the sum of squares versus χ, which was used in the calculation to determine the constants, χ, B, and K of following equation:

$$V_1 = FH(a_1, \chi) + \frac{Ka_1}{1 + Ba_1} \tag{28}$$

where a_1 is the water activity.

Starting with the value of χ calculated by the first program, the values of K and B were calculated by a linear regression analysis of the equation (30) converted from the Langmuir equation (29).

$$S = \frac{c}{p} = \frac{C'_H p}{1 + bp} \tag{29}$$

where: c is the equilibrium concentration of the penetrant in the polymer.

p is the concentration of penetrant surrounding the solid.

$$\frac{1}{W_1^L} = \frac{1}{K} + \frac{B}{K} * \frac{1}{a_1} \tag{30}$$

where: W_1^L is expressed as following equation:

$$W_1^L = W_{\exp} - W^{FH} \tag{31}$$

where W_{exp} is the experimental data and W^{FH} is the Flory-Huggins value.

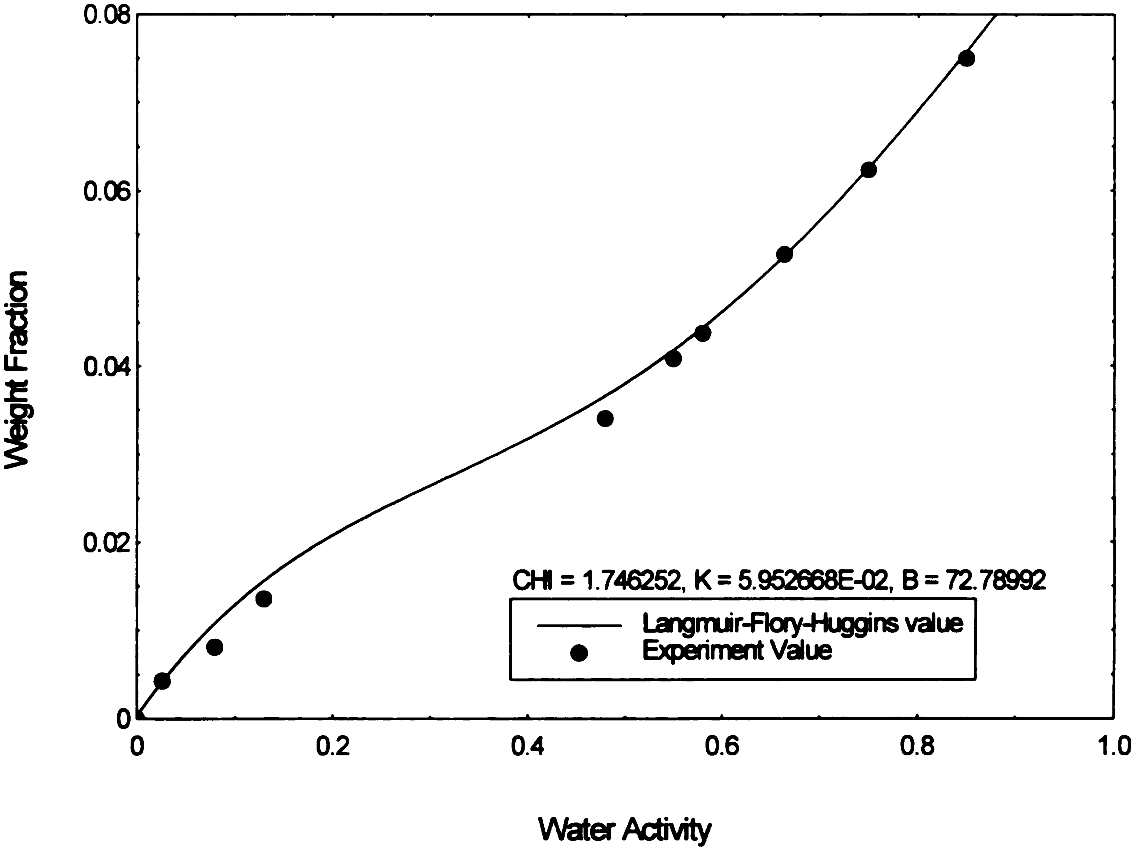


Figure 6: Experiment sorption values and Langmuir-Flory-Huggins best fit

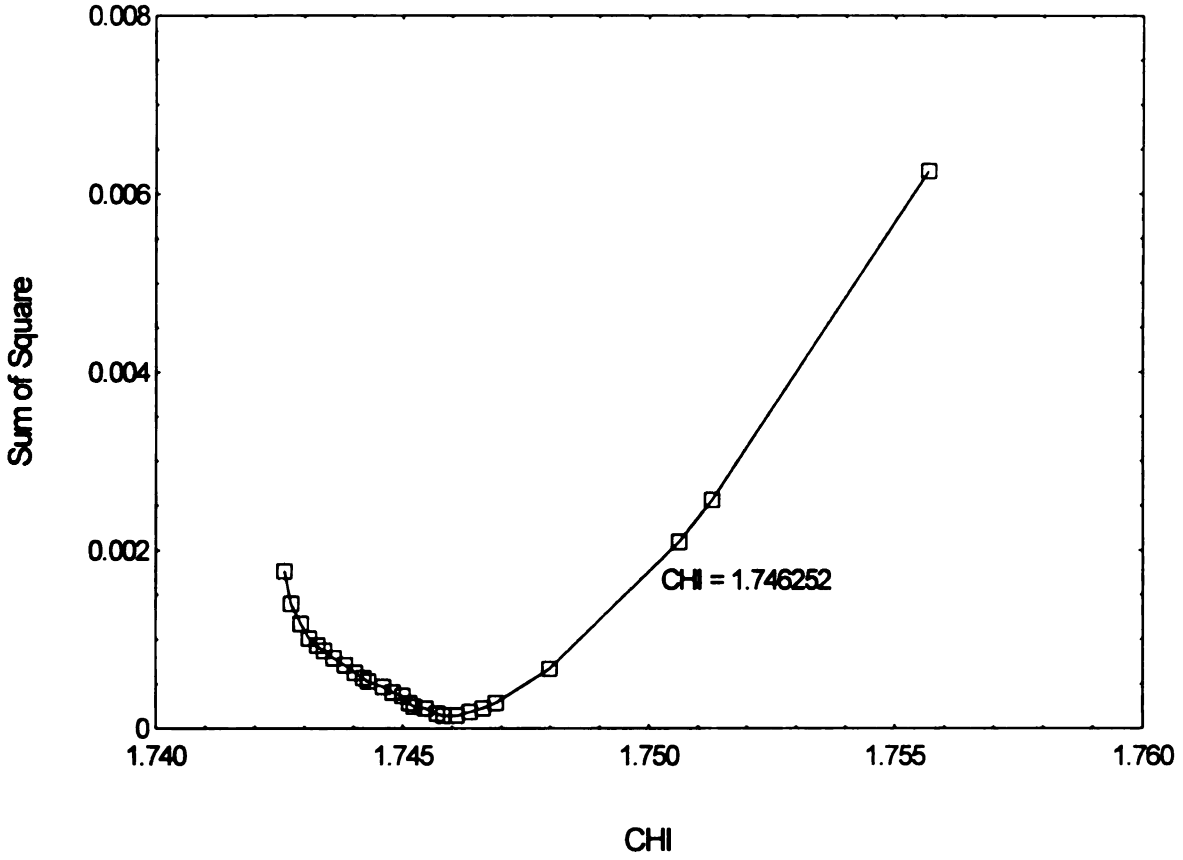


Figure 7: Sum of squares versus χ at 25°C

For a series of χ values, the sum of squares of the difference between the experimental and calculated value were calculated. The values of χ, B, and K were then associated with the minimum value of the sum of squares. The sum of squares was plotted as a function of χ to find the best estimates of the parameters. The χ values of the minimum of the convex curve should be the best estimation of the parameters.

Table 2: Langmuir and Flory-Huggins weight fraction contribution

Water Activity	Experimental Values	F-H Values	Langmuir Values	Total
0.03	0.00295	1.941359E-03	5.609202E-04	2.502280E-03
0.06	0.00428	3.917263E-03	6.654253E-04	4.582689E-03
0.13	0.0099	8.669675E-03	7.396251E-04	0.0094093
0.48	0.0364	3.613822E-02	7.950325E-04	3.693325E-02
0.55	0.0427	4.258816E-02	7.978581E-04	4.338602E-02
0.58	0.0445	4.547782E-02	7.98865E-04	4.627669E-02
0.67	0.0526	5.465947E-02	8.013558E-04	5.546083E-02
0.75	0.0603	6.36753E-02	8.030770E-04	6.437061E-02
0.85	0.0793	7.592858E-02	8.047801E-04	7.673336E-02

Table 3: K, B, and χ parameter for water sorption in Nylon-6, Amorphous Nylon and Amorphous nylon/nylon-6 at 23°C

	K	B	χ
Nylon-6	0.1518	64.26	1.913
Amorphous Nylon	0.5370	58.48	1.712
Nylon Blend	0.0595	72.79	1.746

Table 2 shows the contribution of Langmuir and Flory-Huggins factors over the activity range at 25°C, using the parameter in Figure 2. As shown in Figure 1, the solid curve is best fit curve from Langmuir-Flory-Huggins model to the experimental values at 25°C. The Langmuir-Flory-Huggins model presented by Hernandez et al. (1991) describes accurately the sorption of water by nylon-6 as well as amorphous polyamide, over a broad range of water activity. The initial Langmuir contribution suggests the presence of a limited number of sorption sites which are immediately available to water molecules and following board extent may be indicative of clustering or multi-layer formation at the higher water activity (Kawasaki et al., 1962).

Table 3 illustrates the K, B, and χ parameters of Nylon-6, Amorphous Nylon and Nylon blend.

1.2 Equilibrium Sorption Isotherm in closed containers with salt solution

The glass transition temperature was measured by using differential scanning calorimeter. The samples were equilibrated in closed containers with salt solution. To correlate DSC samples at a given humidity with their moisture content, the moisture content of the films was determined by two methods, Cahn Instrument and closed containers. Both results were comparable. The sorption isotherm values of water weight fraction determined in closed containers and the Cahn Electro-Balance are presented in Table 4.

Figure 8 shows a sorption isotherm plot of water activity versus weight fraction via the two methods. The first is the Cahn instrument and the second is the closed containers with salt solution. The results from the second method were compared with the results from the Cahn Instrument, which correctly confirmed the accuracy of the closed containers with salt solution experiments.

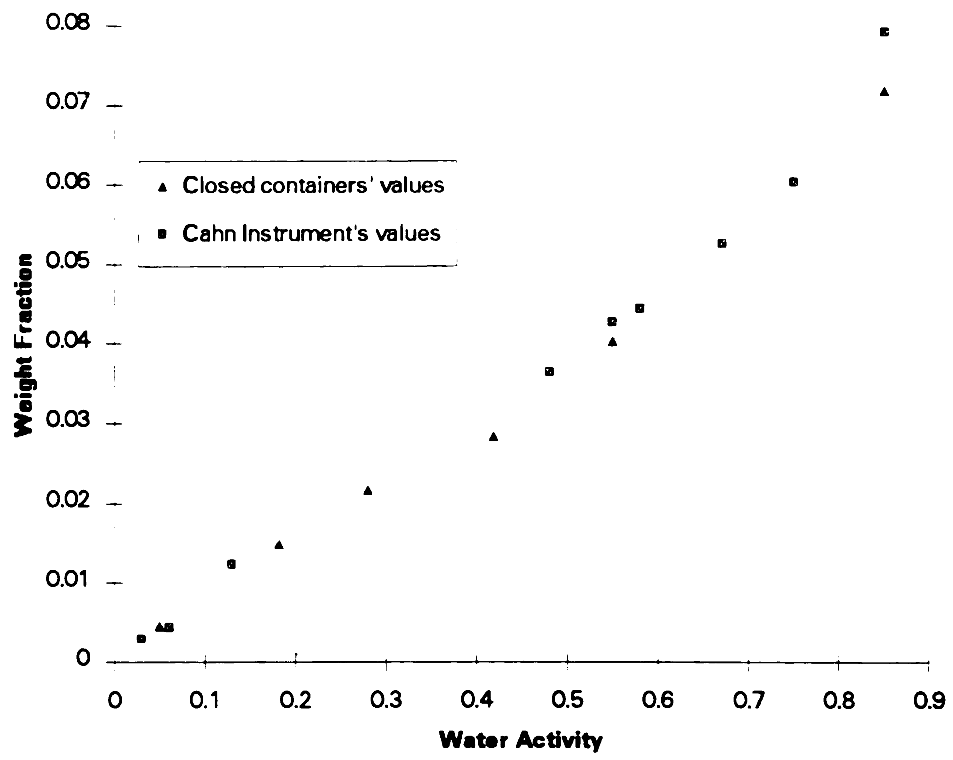


Figure 8: Plot of weight fraction versus water activity distribution of sorption isotherm under various humidity model controlled by salt solution and measured by Cahn Instrument

Table 4: Relative Humidity, weight of samples after drying, weight of samples after conditioning, and weight fraction

RH(%)	Weight after dry (gm)	Weight after condition (gm)	Weight Fraction
18.2	0.0538	0.0542	0.0074349
	0.1022	0.1031	0.0088063
	0.0919	0.0928	0.0097933
28	0.1471	0.1495	0.0163154
	0.1572	0.1603	0.0197201
	0.1165	0.1182	0.0145923
42	0.1468	0.1450	0.0298295
	0.1110	0.1138	0.0252252
	0.1245	0.1279	0.0273092
55	0.1681	0.1734	0.0315289
	0.1776	0.1835	0.0332207
	0.1391	0.1433	0.0301941
85	0.0728	0.0776	0.0659341
	0.1326	0.1411	0.0641026
	0.0838	0.0894	0.0668258

2. OXYGEN PERMEABILITY

Oxygen permeability experiments were carried out at 23°C and within a range of 0 to 0.97 water activity. The plot of permeability from experiments showed that the system seemed to reach two different steady states (Figure 9). This behavior can be explained as a double diffusion mechanism. Accordingly, two simultaneous and independent diffusion processes, one fast and one slow, are proposed to be present during the whole experiment(Gavara and Hernandez, 92). In Figure 10, total oxygen permeability and permeability associated with the slow mechanism as well as the fast mechanism have been plotted as a function of water activity.

The values of flow rate from each run were obtained as a function of time and permeability was calculated from the flow rate at the steady state by rewritten of the solution of Fick's law:

$$\frac{\frac{1}{A}\left(\frac{\Delta M}{\Delta t}\right)_t}{\frac{1}{A}\left(\frac{\Delta M}{\Delta t}\right)_\infty} = \frac{F_t}{F_\infty} = \Phi = \left(\frac{4}{\sqrt{\Pi}}\right) X^{\frac{1}{2}} \sum_{n=1,3,5}^{\infty} \exp\left(-n^2 X\right) \tag{32}$$

or using only the first term as:

$$\Phi = \left(\frac{4}{\sqrt{\Pi}}\right) X^{\frac{1}{2}} \exp(-X) \tag{33}$$

where F (oxygen flow rate) represents $\Delta M/(\Delta t A)$, A is the film surface, $X = l^2/4Dt$ and "ϕ" is the ratio between the flow rate at time t and flow rate at the steady state. For permeability experiments, F values were obtained as a function of time from t = 0 to steady state. A Newton-Raphson method was used to evaluate x from equation (32) or (33) as a

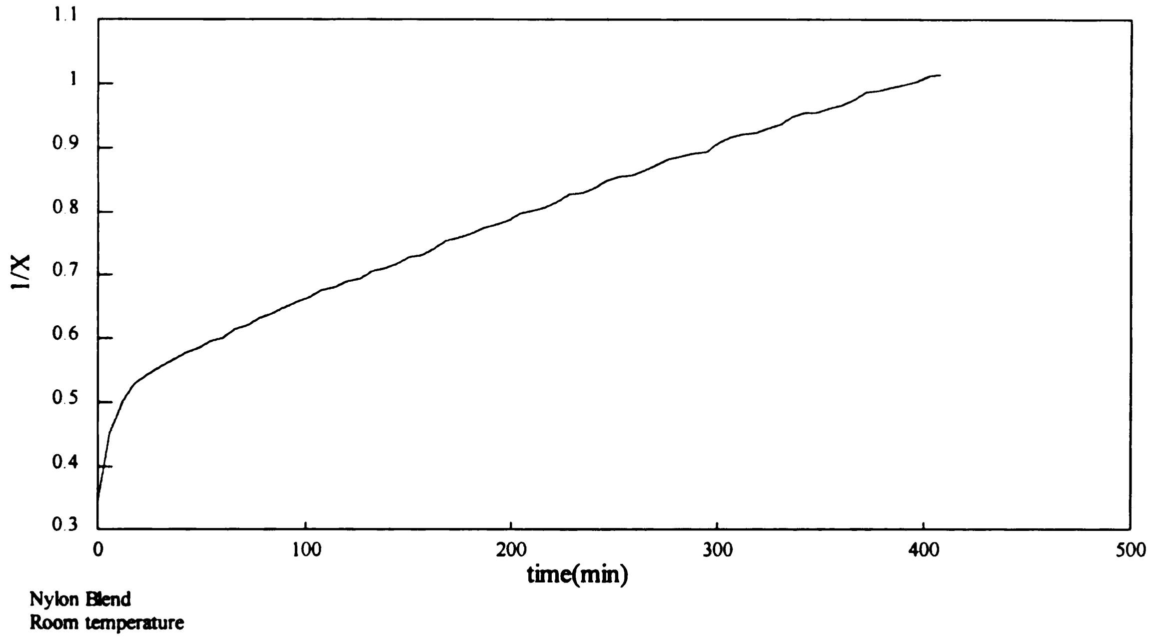


Figure 9: The typical plotted graph between 1/x vs. time of Nylon Blend which it illustrated two mechanism of permeability.

function of time. The diffusion coefficient D is determined from the slope of the straight line of the plot 1/X versus t for values within the range $0.05<\phi<0.97$.

$$D=\frac{l^2}{4Xt}=\frac{(slope)l^2}{4} \tag{34}$$

Otherwise, the permeability , P can be evaluated directly from permeability experiments:

$$P=\frac{Fl}{\Delta P} \tag{35}$$

Assuming that Henry's law applies in the case of oxygen in Nylon, the solubility coefficient, S, can be calculated from (36).

$$P=DS \tag{36}$$

Because of two mechanisms of this experiment, the flow rate fraction is given by the equation (37).

$$\Phi=\frac{F_{s,t}}{F_{s,\infty}}+\frac{F_{f,t}}{F_{f,\infty}}=\left(\frac{4}{\sqrt{\Pi}}\right)\left\{X_f^{\frac{1}{2}}\sum_{n=1,3,5}^{15}\exp(-n^2X_f)+X_s^{\frac{1}{2}}\exp(-n^2X_s)\right\} \tag{37}$$

where "f" and "s" stands for fast and slow mechanism. For each value of D obtained for each mechanism given by equation (38).

$$D_f=\frac{l^2}{4X_ft} \quad and \quad D_s=\frac{l^2}{4X_st} \tag{38}$$

a value of P and S can be calculated

$$P=\frac{Fl}{\Delta P}; \qquad P=P_f+P_s=\frac{F_fl}{\Delta P}+\frac{F_sl}{\Delta P} \tag{39}$$

$$P_f = D_f S_f ; P_s = D_s S_s \tag{40}$$

Experimental values of flow rate were obtained as a function of time and permeability was calculated from the flow rate at the steady state (F_∞) by equation (35). Then the unknown variables in equation (37) X_s, X_f, F_s and F_f were obtained at time t as well as at the steady state. For runs that showed the dual mechanism the procedure for the determination of D and P values was as follows:

For a range of values of F_∞ a series of plots 1/X vs. t was obtained. The highest correlation coefficient ($R^2>0.999$) determined the best value of F_∞. This value of F_∞ was assigned as the flow rate at the steady state for the fast mechanism, $F_{f,\infty}$, Flow associated with the slow diffusion process, $F_{s,\infty}$, was obtained using equation (41).

$$F_\infty = F_{f,\infty} + F_{s,\infty} \tag{41}$$

and D_f from the slope of the plot using equation (38). D_s (or X_s) was calculated by substituting in equation (37) values of D_s and minimizing the error between actual and calculated.

Table 5 shows the slow and fast mechanism values of permeability, diffusion and solubility coefficient of oxygen in amorphous nylon/nylon-6 (20/80) at 23°C.

Table 5: Permeability (P), Solubility (S), and Diffusion Coefficient values of oxygen transport in polymer at 23°C

RH (%)	P cc(STP).cm/m^2.day.atm		S cc O_2(STP)/cc polymer		D$\times10^{10}$ cm^2/second	
	Slow	Fast	Slow	Fast	Slow	Fast
0	0.087987	0.080224	0.228145	1.537161	4.7	0.43
1.4	0.085658	0.077377	0.070815	1.49261	14	0.60
3	0.07893	0.071684	0.06523	0.976084	14	0.85
6	0.075048	0.062109	0.057907	0.845705	15	0.85
10	0.091869	0.034418	0.04623	0.265575	23	1.5
23	0.065473	0.015268	0.044576	0.025245	19	7.0
37	0.091869	0.006987	0.053165	0.047571	20	1.7
50	0.087728	0.01061	0.046153	0.072237	2.2	1.7
74	0.10491	0.006987	0.023213	0.020218	2.5	4.0
97	0.112831	0.001035	0.100455	0.039936	1.3	0.3

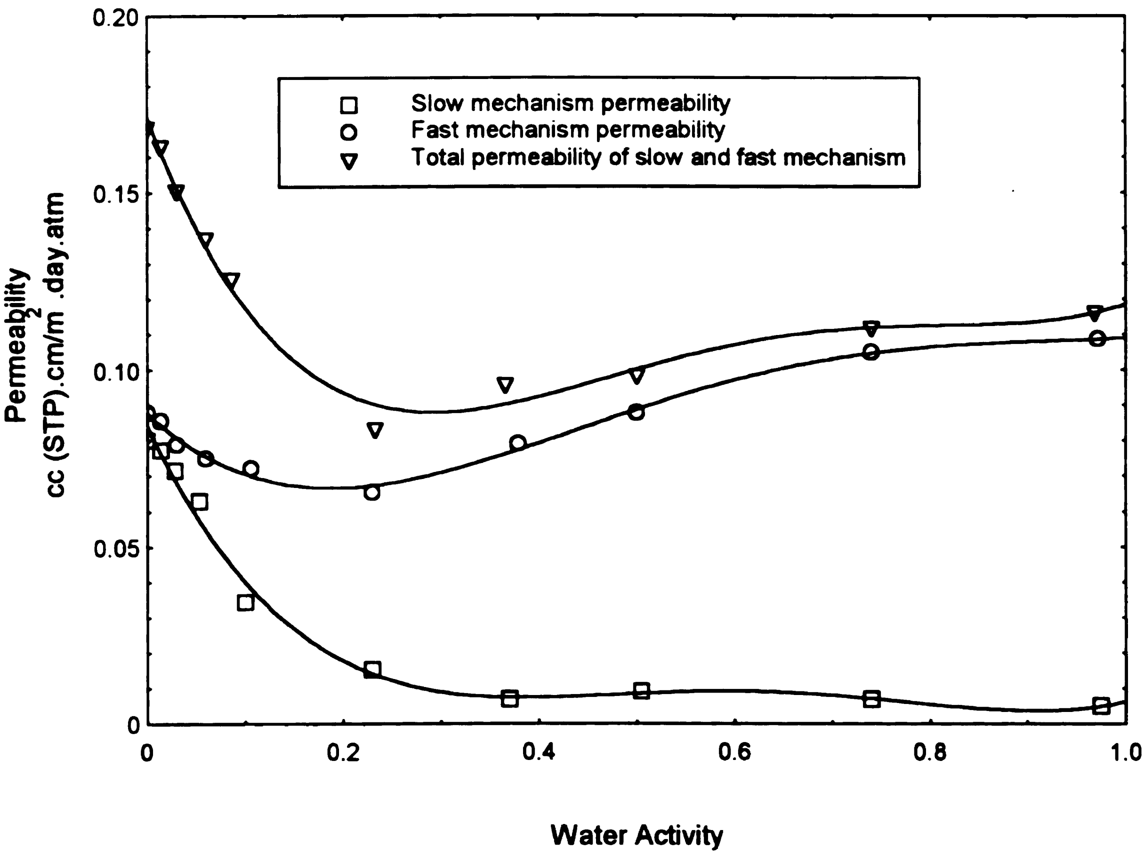


Figure 10: Total oxygen permeability, Fast and Slow mechanism of Nylon blend at 23°C

Figure 10 shows the effect of relative humidity on the permeability coefficient. The diffusion and solubility coefficient values of oxygen in the polymer were obtained from this experiment by equation (34) and (36), respectively (Hernandez et al., 1986). The diffusion coefficient was calculated from a least-squares linear analysis of values from the unsteady state region for each permeability run. Solubility values were calculated from equation (12). The solubility of oxygen (S) is expressed in cc O_2(STP)/cc polymer-water system.

As shown in Figure 10, oxygen permeability decreased in the water activity range of 0 to 0.3 and then increased slightly as the water activity increased.

For comparison reasons, Figure 11 shows the total oxygen permeability of Nylon-6, Amorphous nylon, and nylon blend (amorphous nylon/nylon-6:20/80). The oxygen permeability of the nylon blend is between nylon-6 and amorphous nylon beyond water activity 0.2. It shows that adding 20% amorphous nylon into nylon-6, it does significantly improve the oxygen permeability property of nylon-6 at the high range of water activity.

Figure 12 and 13 present the effect of water activity on the diffusion and the solubility coefficients of oxygen in the blend, as a function of water activity respectively.

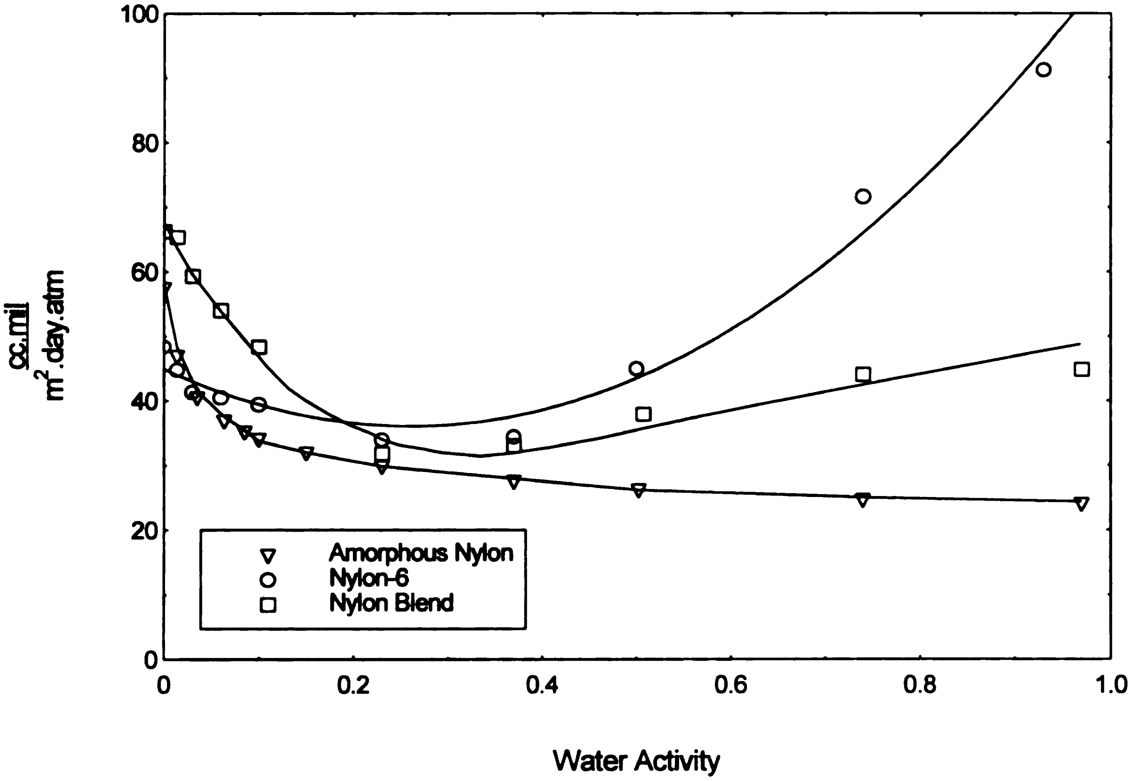


Figure 11: The permeability of Nylon-6, Amorphous Nylon, and Amorphous nylon/Nylon-6 (20:80)

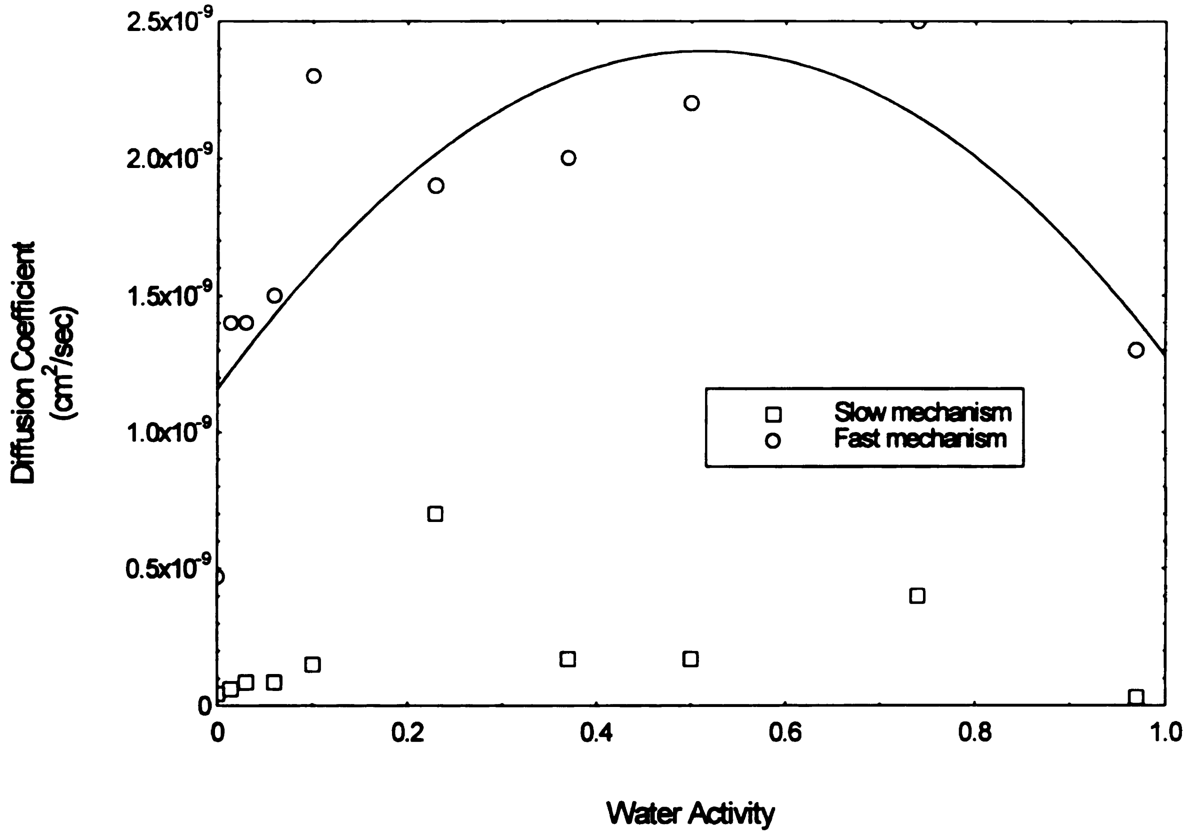


Figure 12: Fast and slow diffusion coefficient values of the nylon blend

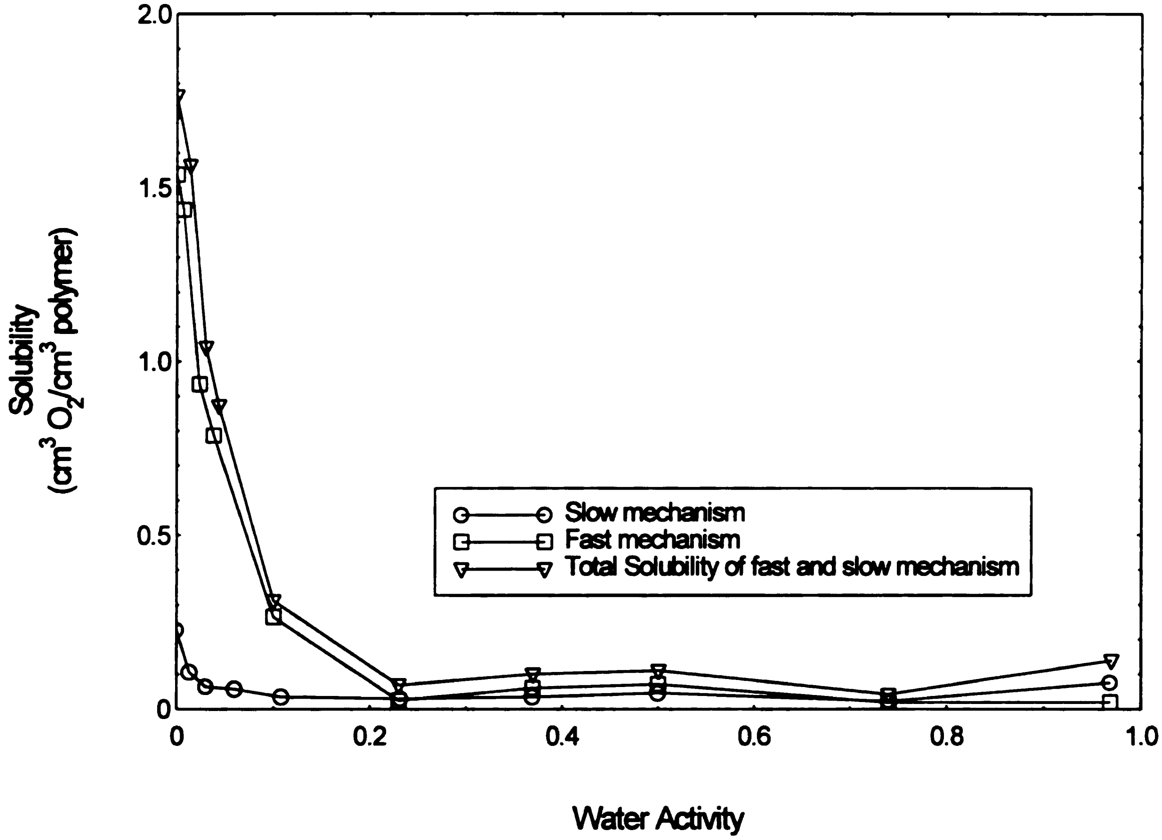


Figure 13: Total, fast, and slow mechanism solubility coefficient values of the blend at 23°C

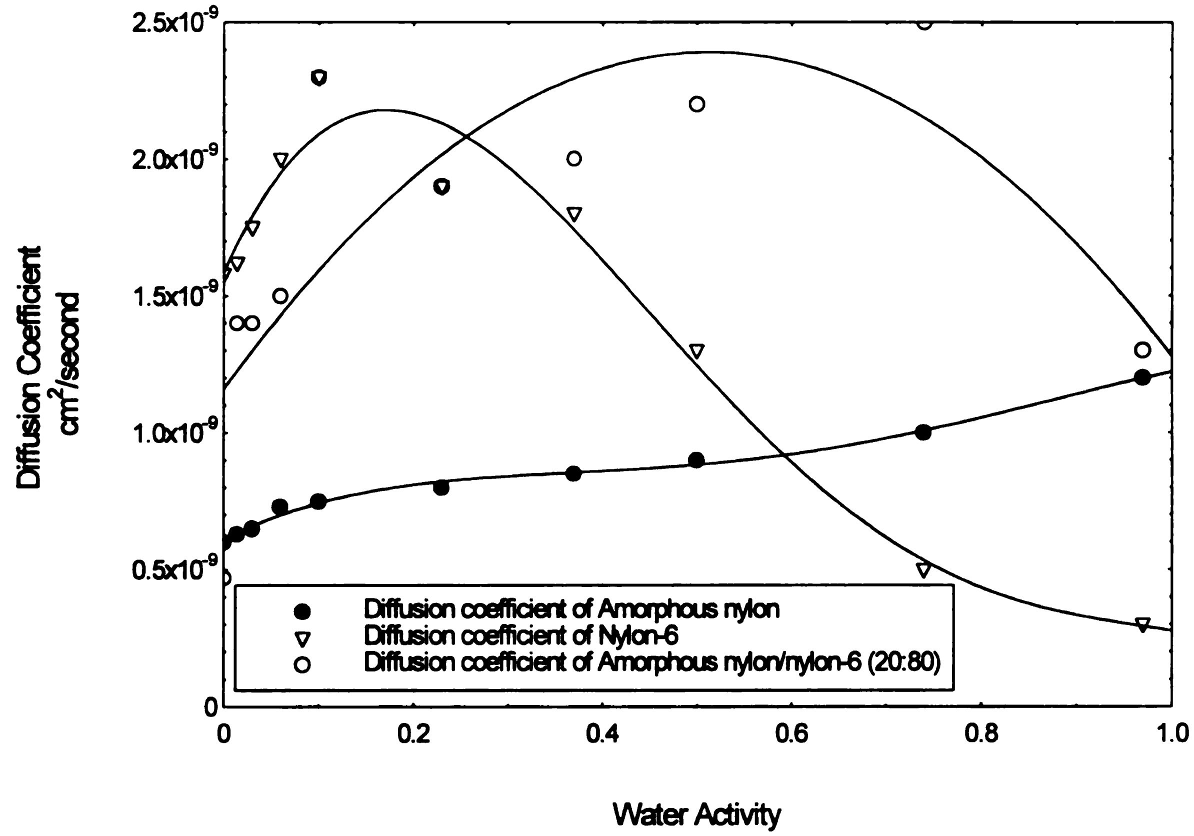


Figure 14: The fast mechanism of diffusion coefficient of Nylon-6, Amorphous Nylon, and the blend

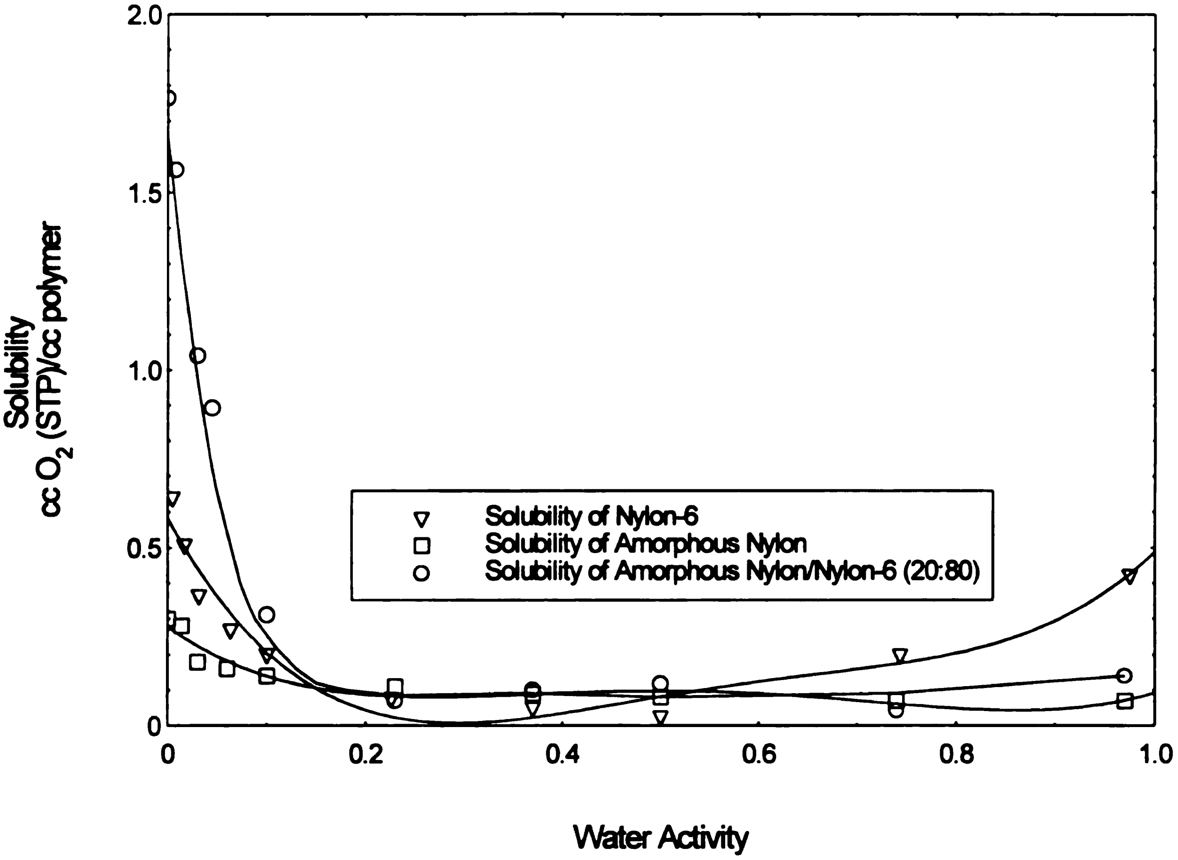


Figure 15: Total solubility of Nylon-6, Amorphous Nylon, and the blend

A statistical analysis using Student's t-test showed that the variable of diffusion coefficient as a function of water activity for both mechanism in Figure 12 are not significant with 95% confidence. Moreover, the diffusion coefficient is independent of the penetrant concentration. Thus, it can be concluded that D values for both mechanisms remain constant as water activity increases. Figure 14 presents fast mechanism of the diffusion coefficient of nylon-6, amorphous nylon, and the blend. The diffusion coefficient of the blend is higher than that of amorphous nylon for all of the water activity range but lower than nylon-6 in the water activity range below 0.3 and higher above 0.3.

As shown in Figure 13, the oxygen solubility coefficient decreased in the range of low water activity (0-0.2), and tended to level off. Solubility values were calculated from the expression,

$$S = \frac{P}{D} \tag{42}$$

Figure 15 illustrates the solubility of oxygen in nylon-6, amorphous nylon, and the blend. As indicated, solubility of oxygen in the blend at a water activity range below 0.2 is higher than nylon-6 and amorphous nylon. Beyond water activity at 0.2, the solubility values of the blend is between the nylon-6 and the amorphous nylon.

3. DIFFERENTIAL SCANNING CALORIMETRY (DSC) METHOD

DSC method was used to determine the percent crystallinity of the blend and glass transition temperature under various water activity. Table 6 shows the glass transition temperature, melting temperature, enthalpy of the glass transition temperature and enthalpy of the melting temperature, and the last column shows the percent crystallinity of the blend. Crystallinity values of the samples were calculated as follows;

$$\%Crystallinity = \frac{\Delta H_f}{\Delta H_b} \tag{43}$$

Where ΔH_b is the calculated heat of fusion of the blend that was calculated by (ΔH_f^* x 0.8) and ΔH_f^* is the heat fusion of 100% crystalline Nylon-6, equal to 195 J/g (Brandrup and Immergut, 1991). The average of the values of percent crystallinity was 32.1% ±1.71%. As a comparison, Table 7 shows the crystallinity of Nylon-6 averages 42.8%. Table 6 shows the values of glass transition temperatures shifted to the lower temperature when samples were exposed to higher relative humidity. The glass transition temperatures of nylons shift to lower temperatures as water content is increased (Starkweather, 1973).

Table 6: The glass transition temperature, melting temperature, enthalpy of glass transition temperature and melting temperature, and % crystallinity of the blend

RH (%)	T_g (°C)	E_g (J/g)	T_m(°C)	E_m (J/g)	%crystall
0	121.6	9.9	206.8	62.4	32.0
5	55.8	3.0	205.9	62.0	31.8
15	46.7	8.0	206.9	60.1	30.8
33	40.8	4.0	206.1	61.1	31.4
65	36.4	2.2	206.5	69.1	35.4
75	35.1	4.9	206.5	60.3	30.9

Table 7: The melting temperature, enthalpy, and % crystallinity of Nylon-6

Sample No.	T_m(°C)[1]	E (J/g)	%crystallinity
1	209.76	85.12	43.65
2	214.99	87.04	44.64
3	215.71	78.12	40.06

---

[1] Melting point of Nylon-6 is between 210 and 220°C (Hill, 87).

CONCLUSIONS

Sorption isotherm values of water in a Nylon blend were obtained over a wide range of water activities at 23°C. A Cahn electrobalance was used to determine the sorption isotherm in the Nylon blend. The moisture content in the samples was determined by the method using closed containers with salt solution. The results from this experiment were then used in the DSC testing. Computer programs were used to determine the values of three parameters (K, B, and χ) of the Langmuir-Flory-Huggins equation to fit a weight fraction versus water activity curve from sorption isotherm experiments. As expected, the moisture isotherm of the blend lay in between the sorption isotherm of Nylon-6 and Nylon 6I/6T.

The oxygen permeability behavior was determined as a function of water humidity at 23°C. The diffusion of oxygen was analyzed according to the bi-model diffusion model proposed by Gavara & Hernandez. Permeability, diffusion, and solubility values were determined for both mechanisms. The oxygen permeability coefficient of the blend decreased in the range of water activity from 0 to 0.3, and then increased as a function of water activity increased.

From the oxygen permeability experiments, the diffusion and solubility coefficient were determined in order to describe accurately the mass transfer behavior of penetrant/barrier systems involving humidities. The solubility of oxygen in the blend tends to reach a plateau as the water activity increases above 0.2.

The decrease of oxygen solubility in polyamide may be interpreted by a decrease the number of active sites available to the oxygen molecules within the polymeric matrix. Although there is no evidence of changing crystallinity with an increase of water activity, the morphology of the polymer blend after water is sorbed might change and create more active sites during the blend sorbing. However, when oxygen permeability of a Nylon blend was compared with oxygen permeability of Nylon-6 and Amorphous Nylon, the oxygen permeability of Nylon blend is between Nylon-6 and Amorphous Nylon. It shows that adding 20% Amorphous Nylon into Nylon-6 can significantly improve the oxygen permeability property of Nylon-6. Differential Scanning Calorimetry (DSC) method was used to determine the crystallinity of the Nylon blend and to find a trend of the glass transition temperature of Nylon blend when it is exposed to various relative humidities. The results indicate that the percent crystallinity of the Nylon blend, 32.1% is less than that of Nylon-6, 42.8%. There is no statistically significant difference in crystallinity associated with an increase of water activity. The glass transition temperature of the Nylon blend shifts to lower temperatures as the water content is increased.

For future work, a study to find an optimum value of percent of blending of Nylon-6/(6I/6T) addition which would encourage a constant oxygen permeability of Nylon would be seen most logical.

```
100
105
110
120
130
140
150
160
A1
170
190
195
200
210
220
225
230
240
250
255
260
270
280
290
300
310
315
320
330
340
350
360
370
380
390
400
410
420
430
440
450
460
560
570
580
590
600
610
615
620
630
640
```

APPENDIX A

Computer Program for Flory-Huggins Model

```
100 REM box kamazu method for flory huggins model
105 REM program written by Dr. R.J. Hernandez, 1988
110 CLS : DIM A1(20), V1(20), ETA(20), X(20)
120 INPUT "HOW MANY POINTS?", N
130 INPUT "HOW MANY ITERATIONS?", ITE
140 INPUT "ENTER THE FIRST ESTIMATION OF CHI", B
150 PRINT "ENTER FIRST A1'S AND THEN V1'S"
160 A1(1) = .03: A1(2) = .06: A1(3) = .13: A1(4) = .48: A1(5) = .55:
A1(6) = .58
170 A1(7) = .67: A1(8) = .75: A1(9) = .85
190 V1(1) = .00295: V1(2) = .00428: V1(3) = .00993: V1(4) = .03641:
195 V1(5) = .04275: V1(6) = .04449: V1(7) = .05264: V1(8) = .06037:
200 V1(9) = .07928
210 PRINT " H", " SO", " S1", " CHI"
220 RL = 0!
225 RL = RL + 1
230 XTX = 0!: XTY = 0!: SO = 0!: S1 = 0!
240 REM EQUATION FOR THE MODEL
250 FOR K = 1 TO N
255 V2 = 1 - V1(K)
260 ETA(K) = V1(K) * EXP(V2 + B * V2 * V2)
270 NEXT K
280 REM EQUATION FOR THE SENSITIVITY COEFF
290 FOR K = 1 TO N
300 X(K) = V1(K) * V2 * V2 * EXP(V2 + B * V2 * V2)
310 NEXT K
315 REM CALCULATE 20, XTX, XTY
320 FOR K = 1 TO N
330 SO = SO + (A1(K) - ETA(K)) * (A1(K) - ETA(K))
340 XTX = XTX + X(K) * X(K)
350 XTY = XTY + X(K) * (A1(K) - ETA(K))
360 NEXT K
370 DELTAB = XTY / XTX
380 REM CALCULATE G
390 G = DELTAB * DELTAB * XTX
400 IF (G < 0!) OR (G = 0!) GOTO 670
410 H = 1!
420 B = B + DELTAB * H
430 REM CALCULATE ETA'S WITH B'S
440 FOR K = 1 TO N
450 ETA(K) = V1(K) * EXP(V2 + B * V2 * V2)
460 NEXT K
560 REM CALCULATE S1
570 FOR K = 1 TO N
580 S1 = S1 + (A1(K) - ETA(K)) * (A1(K) - ETA(K))
590 NEXT K
600 JJ = SO - (2 - (1 / 1.1)) * G
610 IF (S1 < JJ) OR (S1 = JJ) GOTO 640
615 B = B - H * DELTAB
620 H = G / (S1 - SO + 2! * G)
630 B = B + H * DELTAB
640 PRINT H, SO, S1, B
```

```
650 IF (RL < ITE + 1) GOTO 225
660 IF (RL = ITE) GOTO 680
670 PRINT "G =", G
680 END
```

```
100 R
102 R
104 R
105 R
106 R
108 R
110 R
112 R
118 D
121 A
    A
122 A
126 M
127 M
    M
135 I
140 P
145 P
150 F
155 R
160 FO
170 Z
180 Y
190 F
200 F
210 X
215 W
220 N
224 R
230 S
240 N
243 FO
250 R
255 L
260 S
270 S
280 S
290 SS
295 SS
300 N
302 P
303 P
310 R
315 K
320 RE
325 BO
330 B
340 RE
345 SS
350 FO
370 LG
```

APPENDIX B

Computer Program for Langmuir-Flory-Huggins Model

```
100 REM THIS PROGRAM CALCULATES K AND B FOR LANGMUIR
102 REM COMPONENT FRACTION GIVEN CHI THAT HAS BEING OBTAINED
104 REM USING FLORY.BAS IT TAKES THE DIFFERENCE BETWEEN
105 REM EXPERIMENT SORPTION VALUES
106 REM AND DO A LEAST SQUARE ANALYSIS TO GET K AND B
108 REM IT ALSO GIVES THE CORRELATION COEFFICIENT FOR
110 REM THE LINEAR CORRELATION AS WELL AS THE SUM OF SQUARE
112 REM FOR THE EXPERIMENTAL AND LANGMUIR-FLORY-HUGGINS MODEL
118 DIM A(30), W(30), M(30), L(30), LG(30), MFH(30)
121 A(1) = 0!: A(2) = .03: A(3) = .06: A(4) = .13: A(5) = .48:
    A(6) = .55
122 A(7) = .58: A(8) = .67: A(9) = .75: A(10) = .85
126 M(1) = 0!: M(2) = .00295: M(3) = .00428: M(4) = .0099: M(5) = .0364
127 M(6) = .0427: M(7) = .0445: M(8) = .0526: M(9) = .0603:
    M(10) = .0793
135 INPUT "ENTER VALUE OF CHI ", CHI
140 PRINT "CHI VALUE USED=", CHI
145 PRINT "ACTIVITY"; "EXPERIMENT "; " F - H "; " LANG. "; " MFH ";
150 FOR I = 2 TO 10
155 REM FIRST GUESS FOR VOLUME FRACTION: X=A(I)/10
160 FOR II = 1 TO 4
170 Z = 1 - X
180 Y = Z + CHI * Z * Z
190 F = X * EXP(Y) - A(I)
200 FP = EXP(Y) * (1 - X * (2 * CHI * Z + 1))
210 X = X - F / FP
215 W(I) = X
220 NEXT II
224 REM CALCULATE EXPERIMENT F-H TO GIVE LANG. COMP.
230 SA = O: SSA = 0: SL = 0: SSL = 0
240 NEXT I
243 FOR I = 2 TO 10
250 REM LINER REG. TO CALCULATE K&B IN LAPY
255 L(I) = M(I) - W(I)
260 SL = SL + (1 / L(I))
270 SA = SA + (1 / A(I))
280 SAL = SAL + (1 / A(I)) * (1 / L(I))
290 SSA = SSA + (1 / A(I)) * (1 / A(I))
295 SSL = SSL + (1 / L(I)) * (1 / L(I))
300 NEXT I
302 PRINT "SL="; SL, "SA="; SA,
303 PRINT "SAL="; SAL, "SSA="; SSA
310 REM CALCULATE K
315 K = (12 * SSA - SA * SA) / (12 * SAL - SA * SL)
320 REM CALCULATE B/K
325 BOK = ((SL * SSA) - (SA * SAL)) / ((12 * SSA) - SA * SA)
330 B = BOK * K
340 REM CALCULATE SUM OF SQUARE FOR EXPERIMENTAL AND CALCULATED, SST
345 SST = 0
350 FOR I = 2 TO 10
370 LG(I) = K * A(I) / (1 + B * A(I))
```

```
380 SST = SST + ((M(I) - W(I) - LG(I))) ^ 2
400 MFH(I) = W(I) + LG(I)
430 PRINT A(I); M(I); W(I); LG(I); MFH(I)
440 NEXT I
450 SY = 0: SAY = 0
455 FOR I = 2 TO 10
460 SY = SY + (1 / L(I) - BOK - (1 / K) * (1 / A(I))) ^ 2
465 SAY = SAY + (1 / L(I) - SL / 12) ^ 2
468 NEXT I
470 REM CALCULATE CORRLATION COEFFICIENT
475 SR = 1 - SY / SAY
480 PRINT "SUM OF SQUARE ="; SST, "K="; K, "B="; B, "SR="; SR
490 END
```

APPENDIX C

The Calculation Method of Weight Fraction

Water sorption isotherm of Nylon blend were determined by Cahn Instrument. The weight of material was measured and recorded as a function of time by Cahn Instrument. The weight fraction of each relative humidity at steady state was calculated by following equation.

Weight Fraction Calculation

$$Wf = \frac{W_h}{W_p + W_h} \tag{c}$$

where W_f is weight fraction, W_h is weight of water gained, and W_p is weight of polymer dried.

Table 8 shows the weight fraction values were calculated by using equation (c) at each relative humidity at steady state.

Table 8: The calculation of weight fraction at steady state of various humidities

RH (%)	Weight at steady state(gm)	Water gained (gm)	Weight Fraction
0	81.997	0	0
3	82.24	0.243	0.002952
6	82.35	0.353	0.004284
13	82.82	0.823	0.009935
48	85.096	3.099	0.036415
55	85.66	3.663	0.042754
58	85.815	3.818	0.044488
67	86.553	4.556	0.052636
75	87.523	5.526	0.060366
85	89.321	7.324	0.079276

APPENDIX D

The Experimental and Known values in each plot
in the results and dicussions part

Table 9: The total permeability values of Nylon blend, Nylon-6, and Amorphous Nylon

Water Activity	Nylon Blend	Nylon-6	Amorphous Nylon
0.00	66.22441	48.41604	57.5
0.014	65.36811	44.80000	47.0
0.03	59.29685	41.31921	40.0
0.06	53.99882	40.50000	37.0
0.10	49.71929	39.42669	34.5
0.23	31.78780	33.90706	29.9
0.37	33.00000	34.38017	27.6
0.50	38.71575	45.00000	26.4
0.74	44.05394	71.59907	24.7
0.97	44.82913	85.93172	24.2

Table 10: Fast diffusion coefficient values of Nylon blend, Nylon-6 and Amorphous Nylon

Water Activity	Nylon Blend	Nylon-6	Amorphous Nylon
0.00	4.70E-10	1.58E-09	6.00E-10
0.014	1.40E-09	1.62E-09	6.30E-10
0.03	1.40E-09	1.75E-09	6.50E-10
0.06	1.50E-09	2.00E-09	7.30E-10
0.10	2.30E-09	2.30E-09	7.50E-10
0.23	1.90E-09	1.90E-09	8.00E-10
0.37	2.00E-09	1.80E-09	8.50E-10
0.50	2.20E-09	1.30E-09	9.00E-10
0.74	2.50E-09	5.00E-10	1.00E-09
0.97	1.30E-09	3.00E-10	1.20E-09

Ta
an

Table 11: Total solubility coefficient values of Nylon blend, Nylon-6, and Amorphous Nylon

Water Activity	Nylon blend	Amorphous Nylon	Nylon-6
0.000	1.765306	0.30	0.500
0.014	1.563425	0.28	0.470
0.030	1.041314	0.18	0.300
0.060	0.903612	0.16	0.250
0.100	0.311805	0.14	0.200
0.230	0.069821	0.11	0.050
0.370	0.100736	0.90	0.050
0.500	0.118390	0.80	0.025
0.740	0.043431	0.70	0.025
0.970	0.140391	0.70	0.025

Table 12: χ and sum of square value

χ	Sum of square
1.7426	0.00176650
1.74273	0.00140102
1.74293	0.00117766
1.74309	0.00101523
1.74326	0.00093401
1.74339	0.000873096
1.74359	0.000791878
1.74383	0.00071066
1.74403	0.000629442
1.74419	0.000568528
1.74429	0.000527919
1.74459	0.000467005
1.74479	0.000406092
1.74499	0.000365482
1.74512	0.000284264
1.74522	0.000243655
1.74546	0.00022335
1.74569	0.000162437
1.74582	0.000142132
1.74609	0.000142132
1.74625	0.00014132
1.74636	0.000182741
1.74662	0.00022335
1.74689	0.000284264
1.74799	0.000670051
1.75062	0.00209137
1.75128	0.00255838
1.75567	0.00625381

Tab

APPENDIX E

Data of Sorption Isotherm tested by Cahn Instrument

Table 13: Sorption isotherm values from o to 3% RH.

Time (min.)	Weight (gms)
30	81.9972
60	82.1081
90	82.1872
120	82.2211
150	82.2347
180	82.2368
210	82.2388
240	82.2398
270	82.2435
300	82.2437
330	82.2440
360	82.2447
390	82.2449
420	82.2448
450	82.2450
480	82.2441
510	82.2439
540	82.2424
570	82.2435
600	82.2442
630	82.2445
660	82.2443
690	82.2437
720	82.2431
750	82.2429
780	82.2427
810	82.2430
840	82.2437
870	82.2441
900	82.2444
930	82.2424
960	82.2429
990	82.2422

Tab

T
6
8
8
8
9
9
9
9
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
1
2
2
2
2
2
2

Table 14: Sorption Isotherm values from 3 to 6%

Time	Wieght (g)	Time	Wieght (g)	Time	Wieght (g)	Time	Wieght (g)
690	82.2437	2190	82.3470	3690	82.3445	5370	82.3411
720	82.2431	2220	82.3471	3720	82.3458	5400	82.3428
750	82.2429	2250	82.3469	3750	82.3459	5430	82.3435
780	82.2427	2280	82.3467	3780	82.3467	5460	82.3449
810	82.2430	2310	82.3466	3810	82.3489	5490	82.3458
840	82.2437	2340	82.3469	3840	82.3494	5520	82.3467
870	82.2441	2370	82.3468	3870	82.3511	5550	82.3468
900	82.2444	2400	82.3475	3900	82.3522	5580	82.3475
930	82.2424	2430	82.3500	3930	82.3524	5610	82.3477
960	82.2429	2460	82.3520	3960	82.3526	5640	82.3476
990	82.2422	2490	82.3499	3990	82.3528	5670	82.3467
1020	82.2420	2520	82.3475	4020	82.3527	5700	82.3468
1050	82.2415	2550	82.3488	4050	82.3521	5730	82.3434
1080	82.2411	2580	82.3489	4080	82.3519	5760	82.3418
1110	82.2409	2610	82.3457	4110	82.3514	5790	82.3444
1140	82.2253	2640	82.3512	4140	82.3500	5820	82.3459
1170	82.2355	2670	82.3488	4170	82.3487	5850	82.3487
1200	82.2255	2700	82.3463	4200	82.3479	5880	82.3508
1230	82.2529	2730	82.3478	4230	82.3473	5910	82.3522
1260	82.2730	2760	82.3476	4260	82.3465	5940	82.3521
1290	82.2811	2790	82.3474	4290	82.3455	5970	82.3516
1320	82.2862	2820	82.3471	4320	82.3446	6000	82.3555
1350	82.2869	2850	82.3469	4350	82.3456	6030	82.3515
1380	82.2850	2880	82.3444	4380	82.3468	6060	82.3504
1410	82.2866	2910	82.3400	4410	82.3469	6090	82.3475
1440	82.2898	2940	82.3456	4440	82.3477	6120	82.3476
1470	82.2927	2970	82.3468	4470	82.3450	6150	82.3514
1500	82.2958	3000	82.3487	4500	82.3512	6180	82.3526
1530	82.2990	3030	82.3498	4530	82.3525	6210	82.3576
1560	82.3024	3060	82.3574	4560	82.3512	6240	82.3598
1590	82.3056	3090	82.3570	4590	82.3524	6270	82.3580
1620	82.3084	3120	82.3564	4620	82.3500	6300	82.3575
1650	82.3112	3150	82.3562	4650	82.3468	6330	82.3576
1680	82.3145	3180	82.3551	4680	82.3479	6360	82.3588
1710	82.3168	3210	82.3522	4710	82.3502	6390	82.3589
1740	82.3191	3240	82.3501	4740	82.3515	6420	82.3597
1770	82.3225	3270	82.3491	4770	82.3518	6450	82.3595
1800	82.3255	3300	82.3479	4800	82.3542	6480	82.4038
1830	82.3284	3330	82.3476	4830	82.3539	6490	82.4799
1860	82.3309	3360	82.3466	4860	82.3541	6500	82.5363
1890	82.3339	3390	82.3463	4890	82.3527	6510	82.5766
1920	82.3366	3420	82.3461	4920	82.3514	6520	82.6076
1950	82.3396	3450	82.3465	4950	82.3500	6530	82.6323
1980	82.3415	3480	82.3460	4980	82.3487	6540	82.6517
2010	82.3455	3510	82.3459	5010	82.3475	6550	82.6680
2040	82.3465	3540	82.3502	5040	82.3471	6560	82.6794
2070	82.3467	3570	82.3502	5070	82.3462	6570	82.6912
2100	82.3468	3600	82.3488	5280	82.3432	6580	82.7017
2130	82.3469	3630	82.3447	5310	82.3420	6590	82.7117
2160	82.3470	3660	82.3412	5340	82.3400	6600	82.7204

Table

Time (m
63
64
64
64
64
65
65
65
65
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6
6

Table 15: Sorption Isotherm Values from 6 to 13% RH

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
6390	82.3589	6940	82.8596	7390	82.9782	7840	83.0058
6420	82.3597	6950	82.8641	7400	82.9801	7850	82.9773
6450	82.3595	6960	82.8684	7410	82.9831	7860	82.9823
6480	82.4038	6970	82.8722	7420	82.9851	7870	83.0011
6490	82.4799	6980	82.8761	7430	82.9873	7880	83.0086
6500	82.5363	6990	82.8804	7440	82.989	7890	83.0096
6510	82.5766	7000	82.884	7450	82.9912	7900	83.0101
6520	82.6076	7010	82.8881	7460	82.9926	7910	83.0103
6530	82.6323	7020	82.8917	7470	82.9925	7920	83.01
6540	82.6517	7030	82.8934	7480	82.991	7930	83.0106
6550	82.668	7040	82.8953	7490	82.9891	7940	83.011
6560	82.6794	7050	82.8974	7500	82.9869	7950	83.0115
6570	82.6912	7060	82.899	7510	82.9843	7960	83.0115
6580	82.7017	7070	82.9015	7520	82.9813	7970	83.0124
6590	82.7117	7080	82.904	7530	82.9781	7980	83.0127
6600	82.7204	7090	82.9067	7540	82.9921	7990	83.0134
6610	82.7288	7100	82.909	7550	83.008	8000	83.0148
6620	82.7351	7110	82.912	7560	83.0091	8010	83.0171
6630	82.7391	7120	82.9147	7570	83.0058	8020	83.0184
6640	82.744	7130	82.9177	7580	83.0022	8030	83.0208
6650	82.7485	7140	82.9197	7590	82.9996	8040	83.024
6660	82.7514	7150	82.9223	7600	82.998	8050	83.0274
6670	82.757	7160	82.9248	7610	82.9972	8060	83.0306
6680	82.7613	7170	82.9273	7620	82.9963	8070	83.0344
6690	82.767	7180	82.9305	7630	82.9961	8080	83.0379
6700	82.7739	7190	82.933	7640	82.9962	8090	83.0414
6710	82.7809	7200	82.9356	7650	82.9956	8100	83.0438
6720	82.7873	7210	82.9373	7660	82.9964	8110	83.0463
6730	82.7941	7220	82.9408	7670	82.9971	8120	83.049
6740	82.8001	7230	82.9428	7680	82.9968	8130	83.0522
6750	82.8057	7240	82.9447	7690	82.9974	8140	83.0556
6760	82.7954	7250	82.9466	7700	82.9976	8150	83.0588
6770	82.7855	7260	82.9476	7710	82.9982	8160	83.0626
6780	82.7866	7270	82.9492	7720	82.9986	8170	83.067
6790	82.7915	7280	82.9508	7730	82.9996	8180	83.0696
6800	82.7973	7290	82.9526	7740	82.9997	8190	83.0728
6810	82.8034	7300	82.9538	7750	83.0002	8200	83.075
6820	82.8083	7310	82.956	7760	83.0009	8210	83.0782
6830	82.8134	7320	82.9598	7770	83.0021	8220	83.0798
6840	82.8186	7330	82.9626	7780	83.0018	8230	83.0623
6850	82.8235	7340	82.965	7790	83.0027	8240	83.0723
6860	82.8287	7350	82.9689	7800	83.0034	8250	83.0651
6870	82.8335	7360	82.971	7810	83.0035	8270	83.0495
6880	82.8386	7370	82.9733	7820	83.0042	8280	83.0448
6890	82.8427	7380	82.9757	7830	83.0049	8290	83.0409

Time
83
83
83
8
8
8
8
8
8
8

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
8300	83.0385	8650	83.0439	9010	83.0136
8310	83.0378	8660	83.0435	9020	83.0176
8320	83.0376	8670	83.0427	9030	83.0182
8330	83.0376	8680	83.0428	9040	83.0173
8340	83.0378	8690	83.0424	9050	83.0166
8350	83.0381	8700	83.0421	9060	83.0156
8360	83.0377	8710	83.0418	9070	83.0157
8370	83.0372	8720	83.0421	9080	83.0162
8380	83.0372	8730	83.0417	9090	83.016
8390	83.0371	8740	83.0417	9100	83.016
8400	83.0374	8750	83.0412	9110	83.0164
8410	83.0372	8770	83.0413	9120	83.0168
8420	83.0373	8780	83.0412	9130	83.0173
8430	83.0369	8790	83.0413	9140	83.0174
8440	83.0376	8800	83.0415	9150	83.0176
8450	83.0378	8810	83.0417	9160	83.0174
8460	83.0379	8820	83.0415	9170	83.0172
8470	83.0388	8830	83.0412	9180	83.0171
8480	83.0388	8840	83.0414	9190	83.0166
8490	83.0392	8850	83.0409	9200	83.0168
8500	83.0395	8860	83.0412	9210	83.0166
8510	83.0401	8870	83.0407	9220	83.0164
8520	83.0404	8880	83.0399	9230	83.0169
8530	83.0405	8890	83.0388	9240	83.0168
8540	83.0408	8900	83.0386	9250	83.017
8550	83.0409	8910	83.0365	9260	83.0179
8560	83.0422	8920	83.0349	9270	83.0181
8570	83.0423	8930	83.0323	9280	83.0184
8580	83.0426	8940	83.0304	9290	83.0189
8590	83.0426	8950	83.0285	9300	83.0192
8600	83.0427	8960	83.0254	9310	83.0199
8610	83.0434	8970	83.0233	9320	83.0201
8620	83.0435	8980	83.0209	9330	83.0206
8630	83.0443	8990	82.9953	9340	83.0213
8640	83.0442	9000	83.0006	9350	83.0215

Table 16: Sorption Isotherm Values from 13 to 48 % RH

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
9360	83.0222	9800	84.9096	10240	85.0267	10690	85.0757
9370	83.0252	9810	84.9151	10250	85.0278	10700	85.0771
9380	83.1539	9820	84.9213	10260	85.0293	10710	85.0778
9390	83.3451	9830	84.9276	10270	85.0307	10720	85.08
9400	83.5655	9840	84.933	10280	85.0322	10730	85.0816
9410	83.7882	9850	84.9381	10300	85.0349	10740	85.0839
9420	83.9842	9860	84.9345	10310	85.0366	10750	85.0859
9430	84.1458	9870	84.9458	10320	85.0378	10760	85.0887
9440	84.2716	9880	84.9538	10330	85.0389	10770	85.0912
9450	84.3675	9890	84.9592	10340	85.0394	10780	85.094
9460	84.4409	9900	84.9629	10350	85.042	10790	85.0962
9470	84.4975	9910	84.966	10360	85.0435	10800	85.0973
9480	84.5411	9920	84.9694	10370	85.0445	10810	85.098
9490	84.576	9930	84.9725	10380	85.0452	10820	85.0967
9500	84.6058	9940	84.9755	10390	85.0448	10830	85.0973
9510	84.6303	9950	84.9781	10400	85.0443	10840	85.0979
9520	84.6515	9960	84.9806	10410	85.046	10850	85.0013
9530	84.67	9970	84.9826	10420	85.0475	10860	85.0031
9540	84.6863	9980	84.9856	10430	85.0483	10870	85.004
9550	84.7002	9990	84.9872	10440	85.0494	10880	85.0038
9560	84.7128	10000	84.9888	10450	85.0511	10890	85.0038
9570	84.7248	10010	84.9906	10460	85.0522	10900	85.0032
9580	84.7371	10020	84.9922	10470	85.0536	10910	85.0031
9590	84.7485	10030	84.9945	10480	85.0549	10920	85.0033
9600	84.7588	10040	84.9967	10490	85.057	10930	85.0025
9610	84.7692	10050	84.9983	10500	85.0585	10940	85.003
9620	84.7795	10060	85.0005	10510	85.0587	10950	85.0034
9630	84.7767	10070	85.0018	10520	85.06	10960	85.003
9640	84.7975	10080	85.0034	10530	85.0609	10970	85.0035
9650	84.8097	10090	85.0051	10540	85.0625	10980	85.0038
9660	84.8184	10100	85.0056	10550	85.064	10990	85.0042
9670	84.8252	10110	85.0066	10560	85.0654	11000	85.006
9680	84.8331	10120	85.0077	10570	85.0666	11010	85.0075
9690	84.8419	10130	85.0088	10580	85.0675	11020	85.008
9700	84.8492	10140	85.0106	10590	85.0688	11030	85.0089
9710	84.8572	10150	85.0134	10600	85.069	11040	85.0103
9720	84.8649	10160	85.0155	10610	85.0695	11050	85.011
9730	84.8722	10170	85.0166	10620	85.0698	11060	85.0121
9740	84.8783	10180	85.0183	10630	85.0696	11070	85.0124
9750	84.8837	10190	85.0204	10640	85.0706	11080	85.0143
9760	84.8889	10200	85.0211	10650	85.0715	11090	85.0153
9770	84.8953	10210	85.0226	10660	85.0725	11100	85.0162
9780	84.9	10220	85.0245	10670	85.0733	11110	85.0172
9790	84.9052	10230	85.0251	10680	85.0745	11120	85.0177

T

T

Table 17: Sorption Isotherm Values from 48 to 55% RH

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
11130	85.0188	11590	85.4369	12040	85.483	12490	85.5563
11140	85.0588	11600	85.4385	12050	85.484	12500	85.5567
11150	85.1569	11610	85.4399	12060	85.4857	12510	85.5565
11160	85.2142	11620	85.4411	12070	85.4864	12520	85.5561
11170	85.2482	11630	85.4419	12080	85.4883	12530	85.5563
11180	85.2717	11640	85.4421	12090	85.4899	12540	85.5565
11190	85.2895	11650	85.4434	12100	85.4906	12550	85.5562
11200	85.3056	11660	85.4452	12110	85.4919	12560	85.5567
11210	85.3187	11670	85.446	12120	85.4928	12570	85.5565
11220	85.3296	11680	85.4472	12130	85.4936	12580	85.5566
11230	85.3392	11690	85.4485	12140	85.4951	12590	85.5572
11240	85.3472	11700	85.4489	12150	85.4961	12600	85.5569
11250	85.3542	11710	85.4498	12160	85.4975	12610	85.5567
11260	85.3608	11720	85.4501	12170	85.4984	12620	85.557
11270	85.3661	11730	85.4506	12180	85.4995	12630	85.5579
11280	85.3707	11740	85.4508	12190	85.5008	12640	85.5571
11290	85.3753	11750	85.4513	12200	85.5012	12650	85.5572
11300	85.3794	11760	85.4517	12210	85.5025	12660	85.5569
11310	85.3834	11770	85.4523	12220	85.5036	12670	85.5568
11320	85.3861	11780	85.4525	12230	85.5044	12680	85.5577
11330	85.3877	11790	85.4527	12240	85.5057	12690	85.5569
11340	85.3905	11800	85.4535	12250	85.5071	12700	85.558
11350	85.3932	11810	85.4543	12260	85.5083	12710	85.5588
11360	85.3958	11820	85.4551	12270	85.5087	12720	85.5596
11370	85.3982	11830	85.4562	12280	85.5094	12730	85.5598
11380	85.4005	11840	85.4578	12290	85.5095	12740	85.5608
11390	85.4026	11850	85.4584	12300	85.5101	12750	85.5609
11400	85.4039	11860	85.4597	12310	85.5113	12760	85.5611
11410	85.4057	11870	85.4613	12320	85.5134	12770	85.5624
11420	85.4075	11880	85.4618	12330	85.5166	12780	85.5632
11430	85.4091	11890	85.4627	12340	85.5208	12790	85.5635
11440	85.4104	11900	85.463	12350	85.5251	12800	85.5637
11450	85.4127	11910	85.4649	12360	85.5287	12810	85.5641
11460	85.4146	11920	85.4663	12370	85.5321	12820	85.5639
11470	85.4161	11930	85.468	12380	85.5352	12830	85.5649
11480	85.418	11940	85.469	12390	85.538	12840	85.5652
11490	85.4202	11950	85.4706	12400	85.5405	12850	85.5658
11500	85.4219	11960	85.472	12410	85.5431	12860	85.5664
11510	85.4242	11970	85.4732	12420	85.5454	12870	85.5676
11520	85.4258	11980	85.4748	12430	85.5475	12880	85.5679
11530	85.4276	11990	85.4761	12440	85.5491	12890	85.5689
11540	85.4299	12000	85.4779	12450	85.551	12900	85.5689
11550	85.4315	12010	85.4791	12460	85.5527	12910	85.5702
11560	85.4326	12020	85.4805	12470	85.5539	12920	85.5717
11570	85.4338	12030	85.4815	12480	85.555	12930	85.5732

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
12940	85.5741	13430	85.6069	13910	85.6459	14390	85.6595
12950	85.5751	13440	85.6083	13920	85.6468	14400	85.6595
12960	85.5766	13450	85.6097	13930	85.6476	14410	85.6595
12970	85.5773	13460	85.6108	13940	85.6477	14420	85.6595
12980	85.5783	13470	85.6123	13950	85.6486	14430	85.6595
12990	85.5793	13480	85.6136	13960	85.6494	14440	85.6595
13000	85.5805	13490	85.6146	13970	85.6503	14450	85.6595
13010	85.5818	13500	85.6149	13980	85.6508	14460	85.6595
13020	85.5837	13510	85.6156	13990	85.6514	14470	85.6595
13030	85.5858	13520	85.616	14000	85.6527	14480	85.6595
13040	85.5875	13530	85.6169	14010	85.6541	14490	85.6595
13050	85.589	13540	85.6172	14020	85.6551	14500	85.6595
13060	85.5899	13550	85.6185	14030	85.6555	14510	85.6595
13070	85.5903	13560	85.6207	14040	85.6559	14520	85.6595
13080	85.5916	13570	85.6228	14050	85.6563	14530	85.6595
13090	85.592	13580	85.6244	14060	85.6566	14540	85.6595
13100	85.5926	13590	85.6257	14070	85.6569	14550	85.6595
13110	85.5924	13600	85.6269	14080	85.6572	14560	85.6595
13120	85.5921	13610	85.6277	14090	85.6575	14570	85.6595
13130	85.5929	13620	85.628	14100	85.6578	14580	85.6595
13140	85.5937	13630	85.6287	14110	85.6581	14590	85.6595
13150	85.5944	13640	85.6296	14120	85.6583	14600	85.6595
13160	85.5949	13650	85.6302	14130	85.6585	14610	85.6595
13170	85.5951	13660	85.6307	14140	85.6587	14620	85.6595
13180	85.596	13670	85.6316	14150	85.6589	14630	85.6595
13190	85.5961	13680	85.6327	14160	85.6591	14640	85.6595
13200	85.5963	13690	85.6331	14170	85.6593	14650	85.6595
13210	85.5961	13700	85.6342	14180	85.6594	14660	85.6595
13220	85.5965	13710	85.6347	14190	85.6594	14670	85.6595
13230	85.5974	13720	85.6348	14200	85.6596	14680	85.6595
13240	85.5974	13730	85.6362	14210	85.6594	14690	85.6595
13250	85.5987	13740	85.6367	14220	85.6595	14700	85.6595
13260	85.5991	13750	85.6382	14230	85.6596	14710	85.6595
13270	85.5996	13760	85.6387	14240	85.6595	14720	85.6595
13280	85.5999	13770	85.6386	14250	85.6594	14730	85.6595
13290	85.6001	13780	85.6403	14260	85.6595	14740	85.6595
13300	85.6003	13790	85.6405	14270	85.6595	14750	85.6595
13310	85.6004	13800	85.6409	14280	85.6595	14760	85.6595
13320	85.603	13810	85.6413	14290	85.6595	14770	85.6595
13330	85.6034	13820	85.6416	14300	85.6595	14780	85.6595
13340	85.6032	13830	85.641	14310	85.6595	14790	85.6595
13350	85.6038	13840	85.6417	14320	85.6595	14800	85.6595
13360	85.6035	13850	85.6424	14330	85.6595	14810	85.6595
13370	85.6041	13860	85.6434	14340	85.6595	14820	85.6595
13380	85.6041	13870	85.6435	14350	85.6595	14830	85.6596
13390	85.6045	13880	85.6445	14360	85.6595	14840	85.6596
13400	85.6047	13890	85.6453	14370	85.6595	14850	85.6596
13410	85.6057	13900	85.6449	14380	85.6595	14860	85.6596

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
14870	85.6596	15360	85.6596	15840	85.6596	16320	85.6596
14880	85.6596	15370	85.6596	15850	85.6596	16330	85.6596
14890	85.6596	15380	85.6596	15860	85.6596	16340	85.6596
14900	85.6596	15390	85.6596	15870	85.6596	16350	85.6596
14910	85.6596	15400	85.6596	15880	85.6596	16360	85.6596
14920	85.6596	15410	85.6596	15890	85.6596	16370	85.6596
14930	85.6596	15420	85.6596	15900	85.6596	16380	85.6596
14940	85.6596	15430	85.6596	15910	85.6596	16390	85.6596
14950	85.6596	15440	85.6596	15920	85.6596	16400	85.6596
14960	85.6596	15450	85.6596	15930	85.6596	16410	85.6596
14970	85.6596	15460	85.6596	15940	85.6596	16420	85.6596
14980	85.6596	15470	85.6596	15950	85.6596	16430	85.6596
14990	85.6596	15480	85.6596	15960	85.6596	16440	85.6596
15000	85.6596	15490	85.6596	15970	85.6596	16450	85.6596
15010	85.6596	15500	85.6596	15980	85.6596	16460	85.6596
15020	85.6596	15510	85.6596	15990	85.6596	16470	85.6596
15030	85.6596	15520	85.6596	16000	85.6596	16480	85.6596
15040	85.6596	15530	85.6596	16010	85.6596	16490	85.6596
15050	85.6596	15540	85.6596	16020	85.6596	16500	85.6596
15060	85.6596	15550	85.6596	16030	85.6596	16510	85.6596
15070	85.6596	15560	85.6596	16040	85.6596	16520	85.6596
15080	85.6596	15570	85.6596	16050	85.6596	16530	85.6596
15090	85.6596	15580	85.6596	16060	85.6596	16540	85.6596
15100	85.6596	15590	85.6596	16070	85.6596	16550	85.6596
15110	85.6596	15600	85.6596	16080	85.6596	16560	85.6596
15120	85.6596	15610	85.6596	16090	85.6596	16570	85.6596
15130	85.6596	15620	85.6596	16100	85.6596	16580	85.6596
15140	85.6596	15630	85.6596	16110	85.6596	16590	85.6596
15150	85.6596	15640	85.6596	16120	85.6596	16600	85.6596
15160	85.6596	15650	85.6596	16130	85.6596	16610	85.6596
15170	85.6596	15660	85.6596	16140	85.6596	16620	85.6596
15180	85.6596	15670	85.6596	16150	85.6596	16630	85.6596
15190	85.6596	15680	85.6596	16160	85.6596	16640	85.6596
15200	85.6596	15690	85.6596	16170	85.6596	16650	85.6596
15210	85.6596	15700	85.6596	16180	85.6596	16660	85.6596
15220	85.6596	15710	85.6596	16190	85.6596	16670	85.6596
15230	85.6596	15720	85.6596	16200	85.6596	16680	85.6596
15240	85.6596	15730	85.6596	16210	85.6596	16690	85.6596
15250	85.6596	15740	85.6596	16220	85.6596	16700	85.6596
15260	85.6596	15750	85.6596	16230	85.6596	16710	85.6596
15270	85.6596	15760	85.6596	16240	85.6596	16720	85.6596
15280	85.6596	15770	85.6596	16250	85.6596	16730	85.6596
15290	85.6596	15780	85.6596	16260	85.6596	16740	85.6596
15300	85.6596	15790	85.6596	16270	85.6596	16750	85.6596
15310	85.6596	15800	85.6596	16280	85.6596	16760	85.6596
15320	85.6596	15810	85.6596	16290	85.6596	16770	85.6596
15330	85.6596	15820	85.6596	16300	85.6596	16780	85.6596
15340	85.6596	15830	85.6596	16310	85.6596	16790	85.6596

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
15350	85.6596	16580	85.6596	16830	85.6596	17110	85.6596
16320	85.6596	16590	85.6596	16840	85.6596	17120	85.6596
16330	85.6596	16600	85.6596	16850	85.6596	17130	85.6596
16340	85.6596	16610	85.6596	16860	85.6596	17140	85.6596
16350	85.6596	16620	85.6596	16870	85.6596	17150	85.6596
16360	85.6596	16630	85.6596	16880	85.6596	17160	85.6596
16370	85.6596	16640	85.6596	16890	85.6596	17170	85.6596
16380	85.6596	16650	85.6596	16900	85.6596	17180	85.6596
16390	85.6596	16660	85.6596	16910	85.6596	17190	85.6596
16400	85.6596	16670	85.6596	16920	85.6596	17200	85.6596
16410	85.6596	16680	85.6596	16930	85.6596	17210	85.6596
16420	85.6596	16690	85.6596	16940	85.6596	17220	85.6596
16430	85.6596	16700	85.6596	16950	85.6596	17230	85.6596
16440	85.6596	16710	85.6596	16960	85.6596	17240	85.6596
16450	85.6596	16720	85.6596	16970	85.6596	17250	85.6596
16460	85.6596	16730	85.6596	16980	85.6596	17260	85.6596
16470	85.6596	16740	85.6596	16990	85.6596	17270	85.6596
16480	85.6596	16750	85.6596	17000	85.6596	17280	85.6596
16490	85.6596	16760	85.6596	17010	85.6596	17290	85.6596
16500	85.6596	16770	85.6596	17020	85.6596	17300	85.6596
16510	85.6596	16780	85.6596	17030	85.6596	17310	85.6596
16520	85.6596	16770	85.6596	17050	85.6596	17320	85.6596
16530	85.6596	16780	85.6596	17060	85.6596	17330	85.6596
16540	85.6596	16790	85.6596	17070	85.6596	17340	85.6596
16550	85.6596	16800	85.6596	17080	85.6596	17350	85.6596
16560	85.6596	16810	85.6596	17090	85.6596	17360	85.6596
16570	85.6596	16820	85.6596	17100	85.6596	17370	85.6596

Table 18: Sorption Isotherm Values form 58 to 67% RH

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
17380	85.6596	17830	86.2293	18280	86.31	18730	86.3312
17390	85.6596	17840	86.2302	18290	86.3123	18740	86.3357
17400	85.6596	17850	86.2311	18300	86.3137	18750	86.339
17410	85.6596	17860	86.2319	18310	86.3151	18760	86.3429
17420	85.6596	17870	86.2325	18320	86.3161	18770	86.3468
17430	85.6596	17880	86.2331	18330	86.3162	18780	86.3505
17440	85.6596	17890	86.2336	18340	86.3159	18790	86.3547
17450	85.6596	17900	86.2345	18350	86.3151	18800	86.3596
17460	85.6596	17910	86.2348	18360	86.3142	18810	86.3644
17470	85.6596	17920	86.2356	18370	86.3122	18820	86.3685
17480	85.6596	17930	86.2362	18380	86.3113	18830	86.3724
17490	85.6596	17940	86.2373	18390	86.3138	18840	86.376
17500	85.6596	17950	86.2382	18400	86.3144	18850	86.3798
17510	85.7498	17960	86.2395	18410	86.3155	18860	86.3835
17520	85.8535	17970	86.2407	18420	86.3171	18870	86.3865
17530	85.9503	17980	86.242	18430	86.3181	18880	86.3884
17540	86.0393	17990	86.2434	18440	86.3193	18890	86.3911
17550	86.1227	18000	86.2453	18450	86.3196	18900	86.3931
17560	86.1547	18010	86.2472	18460	86.3202	18910	86.3969
17570	86.1774	18020	86.2487	18470	86.321	18920	86.3986
17580	86.1923	18030	86.2501	18480	86.3215	18930	86.4017
17590	86.1954	18040	86.2523	18490	86.3211	18940	86.4048
17600	86.1987	18050	86.2547	18500	86.3209	18950	86.4082
17610	86.1995	18060	86.2561	18510	86.3208	18960	86.4117
17620	86.2	18070	86.2581	18520	86.32	18970	86.4152
17630	86.2158	18080	86.2605	18530	86.3197	18980	86.4189
17640	86.2581	18090	86.2619	18540	86.3193	18990	86.4222
17650	86.2653	18100	86.2639	18550	86.3184	19000	86.425
17660	86.2644	18110	86.2658	18560	86.317	19010	86.4286
17670	86.2589	18120	86.2674	18570	86.316	19020	86.4317
17680	86.2533	18130	86.2692	18580	86.3149	19030	86.4351
17690	86.2477	18140	86.271	18590	86.314	19040	86.4386
17700	86.243	18150	86.2731	18600	86.3135	19050	86.4418
17710	86.2388	18160	86.2748	18610	86.3128	19060	86.4363
17720	86.2357	18170	86.2758	18620	86.3128	19070	86.4444
17730	86.2331	18180	86.2775	18630	86.3131	19080	86.4466
17740	86.2309	18190	86.2799	18640	86.3129	19090	86.4475
17750	86.2292	18200	86.2832	18650	86.3137	19100	86.4473
17760	86.2284	18210	86.2864	18660	86.3149	19110	86.4474
17770	86.2277	18220	86.2901	18670	86.3166	19120	86.4478
17780	86.2273	18230	86.2932	18680	86.3183	19130	86.4488
17790	86.2274	18240	86.2971	18690	86.3203	19140	86.4497
17800	86.2278	18250	86.3007	18700	86.3228	19150	86.4523
17810	86.2285	18260	86.304	18710	86.3257	19160	86.4544
17820	86.229	18270	86.3068	18720	86.3275	19170	86.457

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
19180	86.4602	19660	86.5391	20130	86.5433	20600	86.5424
19190	86.4625	19670	86.5406	20140	86.5432	20610	86.5421
19200	86.4645	19680	86.5399	20150	86.5435	20620	86.5435
19210	86.4676	19690	86.5399	20160	86.5437	20630	86.5441
19220	86.4703	19700	86.5394	20170	86.5447	20640	86.5444
19230	86.4724	19710	86.539	20180	86.545	20650	86.5483
19240	86.4748	19720	86.5394	20190	86.5441	20660	86.5488
19250	86.4772	19730	86.5398	20200	86.5443	20670	86.5499
19260	86.4799	19740	86.5409	20210	86.5444	20680	86.545
19270	86.4835	19750	86.5399	20220	86.5439	20690	86.5452
19280	86.4869	19760	86.541	20230	86.5438	20700	86.5499
19290	86.4885	19770	86.5413	20240	86.5446	20710	86.5467
19300	86.491	19780	86.5402	20250	86.5448	20720	86.5481
19310	86.4931	19790	86.5415	20260	86.5441	20730	86.5435
19320	86.4952	19800	86.5417	20270	86.5443	20740	86.5455
19330	86.4973	19810	86.5417	20280	86.5445	20750	86.5487
19340	86.4996	19820	86.5419	20290	86.5437	20760	86.5496
19350	86.5022	19830	86.5408	20300	86.5435	20770	86.545
19360	86.5044	19840	86.5422	20310	86.544	20780	86.545
19370	86.5062	19850	86.5419	20320	86.5447	20790	86.5451
19380	86.5081	19860	86.5423	20330	86.5448	20800	86.5453
19390	86.5111	19870	86.5409	20340	86.545	20810	86.545
19400	86.5131	19880	86.5425	20350	86.5443	20820	86.5449
19410	86.5148	19890	86.5425	20360	86.5447	20830	86.5437
19420	86.517	19900	86.5428	20370	86.5453	20840	86.55
19430	86.5195	19910	86.542	20380	86.545	20850	86.5502
19440	86.522	19920	86.5421	20390	86.5449	20860	86.5492
19450	86.5242	19930	86.5428	20400	86.5446	20870	86.5465
19460	86.5266	19940	86.5431	20410	86.5443	20880	86.5512
19470	86.5288	19950	86.5444	20420	86.5444	20890	86.5523
19480	86.531	19960	86.5433	20430	86.5439	20900	86.551
19490	86.5336	19970	86.5421	20440	86.544	20910	86.5502
19500	86.5352	19980	86.5423	20450	86.5445	20920	86.5486
19510	86.5366	19990	86.5425	20460	86.545	20930	86.5475
19520	86.537	20000	86.5442	20470	86.5452	20940	86.5477
19530	86.5376	20010	86.5445	20480	86.5432	20950	86.5479
19540	86.5389	20020	86.5429	20490	86.5438	20960	86.5479
19550	86.5389	20030	86.5431	20500	86.5439	20970	86.5479
19560	86.5389	20040	86.5447	20510	86.5445	20980	86.5486
19570	86.5391	20050	86.5445	20520	86.5437	20990	86.5487
19580	86.5388	20060	86.5443	20530	86.5429	21000	86.5487
19590	86.5393	20070	86.5438	20540	86.542	21010	86.5494
19600	86.5381	20080	86.5439	20550	86.5419	21020	86.5482
19610	86.5385	20090	86.5449	20560	86.54	21030	86.5482
19620	86.5388	20100	86.5445	20570	86.5387	21040	86.5477
19630	86.539	20110	86.5443	20580	86.5402	21050	86.5489
19640	86.5393	20120	86.5431	20590	86.5411	21060	86.5475

TIme (Min)	Weight (g)	TIme (Min)	Weight (g)	TIme (Min)	Weight (g)	TIme (Min)	Weight (g)
21080	86.5487	21260	86.5512	21440	86.5497	21620	86.5507
21090	86.5511	21270	86.5513	21450	86.5512	21630	86.5509
21100	86.5513	21280	86.5526	21460	86.5513	21640	86.5515
21110	86.5508	21290	86.5526	21470	86.5505	21650	86.5522
21120	86.5506	21300	86.5519	21480	86.5509	21660	86.5517
21130	86.5509	21310	86.5487	21490	86.5512	21670	86.5515
21140	86.5529	21320	86.5495	21500	86.5512	21680	86.5519
21150	86.5527	21330	86.5498	21510	86.5515	21690	86.5518
21160	86.5515	21340	86.5512	21520	86.5517	21700	86.5512
21170	86.5503	21350	86.5513	21530	86.552	21710	86.5508
21180	86.5497	21360	86.5504	21540	86.5514	21720	86.5507
21190	86.5496	21370	86.5509	21550	86.5525	21730	86.5504
21200	86.5494	21380	86.5512	21560	86.5513	21740	86.5511
21210	86.5501	21390	86.5522	21570	86.5514	21750	86.5514
21220	86.5509	21400	86.5498	21580	86.5524	21760	86.5516
21230	86.5509	21410	86.5468	21590	86.5549	21770	86.5522
21240	86.5509	21420	86.5479	21600	86.5504	21780	86.5524
21250	86.5515	21430	86.5488	21610	86.5506	21780	86.5524

Table 19: Sorption Isotherm Values from 67 to 75% RH

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
21790	86.5528	22240	86.9848	22690	87.0939	23140	87.1384
21800	86.553	22250	86.99	22700	87.096	23150	87.1399
21810	86.5766	22260	86.9939	22710	87.0975	23160	87.1409
21820	86.6147	22270	86.9994	22720	87.0992	23170	87.1421
21830	86.6501	22280	87.0024	22730	87.1014	23180	87.144
21840	86.6815	22290	87.0057	22740	87.1031	23190	87.1455
21850	86.5569	22300	87.008	22750	87.1048	23200	87.1437
21860	86.5856	22310	87.0115	22760	87.1053	23210	87.1455
21870	86.6124	22320	87.0146	22770	87.1074	23220	87.1471
21880	86.6361	22330	87.018	22780	87.1071	23230	87.1467
21890	86.6574	22340	87.0209	22790	87.1084	23240	87.1444
21900	86.6775	22350	87.0237	22800	87.1083	23250	87.1483
21910	86.6959	22360	87.027	22810	87.1089	23260	87.1515
21920	86.7133	22370	87.0295	22820	87.1102	23270	87.1527
21930	86.7286	22380	87.0323	22830	87.1119	23280	87.1535
21940	86.745	22390	87.035	22840	87.1129	23290	87.1545
21950	86.7585	22400	87.037	22850	87.1138	23300	87.155
21960	86.7716	22410	87.0388	22860	87.1144	23310	87.155
21970	86.785	22420	87.0426	22870	87.1146	23320	87.1559
21980	86.7968	22430	87.0449	22880	87.115	23330	87.1577
21990	86.8086	22440	87.0468	22890	87.1157	23340	87.1585
22000	86.8198	22450	87.0494	22900	87.1162	23350	87.1588
22010	86.8303	22460	87.0507	22910	87.1167	23360	87.1602
22020	86.839	22470	87.0528	22920	87.0432	23370	87.1605
22030	86.8494	22480	87.0557	22930	87.0819	23380	87.1622
22040	86.8593	22490	87.0556	22940	87.1116	23390	87.1636
22050	86.8684	22500	87.06	22950	87.1207	23400	87.1645
22060	86.8762	22510	87.0621	22960	87.1244	23410	87.1654
22070	86.8842	22520	87.061	22970	87.1268	23420	87.166
22080	86.8938	22530	87.0629	22980	87.1267	23430	87.1665
22090	86.8984	22540	87.0645	22990	87.1283	23440	87.1674
22100	86.9067	22550	87.0664	23000	87.1293	23450	87.1684
22110	86.914	22560	87.0689	23010	87.1301	23460	87.1695
22120	86.9209	22570	87.0712	23020	87.1303	23470	87.1714
22130	86.9282	22580	87.0725	23030	87.1303	23480	87.1727
22140	86.9342	22590	87.0743	23040	87.1312	23490	87.174
22150	86.9402	22600	87.0766	23050	87.1308	23500	87.1752
22160	86.9462	22610	87.0784	23060	87.1313	23510	87.1763
22170	86.9518	22620	87.0808	23070	87.1323	23520	87.1768
22180	86.9576	22630	87.0833	23080	87.1327	23530	87.1777
22190	86.9632	22640	87.0847	23090	87.1338	23540	87.1795
22200	86.968	22650	87.0862	23100	87.1346	23550	87.1813
22210	86.9728	22660	87.0884	23110	87.1355	23560	87.1817
22220	86.9714	22670	87.0905	23120	87.1365	23570	87.1824
22230	86.9787	22680	87.0927	23130	87.1375	23580	87.1847

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
23140	87.1384	23630	87.191	24110	87.2385	24590	87.2869
23150	87.1399	23640	87.1915	24120	87.2403	24600	87.2884
23160	87.1409	23650	87.1928	24130	87.2417	24610	87.2887
23170	87.1421	23660	87.1937	24140	87.2427	24620	87.2897
23180	87.144	23670	87.1943	24150	87.2434	24630	87.2908
23190	87.1455	23680	87.1952	24160	87.2437	24640	87.292
23200	87.1437	23690	87.1971	24170	87.2445	24650	87.2928
23210	87.1455	23700	87.2004	24180	87.2455	24660	87.2931
23220	87.1471	23710	87.2001	24190	87.2451	24670	87.2949
23230	87.1467	23720	87.2017	24200	87.2459	24680	87.2957
23240	87.1444	23730	87.2027	24210	87.2471	24690	87.2958
23250	87.1483	23740	87.2035	24220	87.2476	24700	87.2972
23260	87.1515	23750	87.2047	24230	87.2484	24710	87.2977
23270	87.1527	23760	87.2056	24240	87.2491	24720	87.2976
23280	87.1535	23770	87.2064	24250	87.2491	24730	87.2991
23290	87.1545	23780	87.2068	24260	87.2506	24740	87.3002
23300	87.155	23790	87.2078	24270	87.2514	24750	87.3014
23310	87.155	23800	87.2091	24280	87.2528	24760	87.302
23320	87.1559	23810	87.2098	24290	87.2539	24770	87.3042
23330	87.1577	23820	87.2112	24300	87.2545	24780	87.3049
23340	87.1585	23830	87.2123	24310	87.2562	24790	87.3056
23350	87.1588	23840	87.2134	24320	87.2576	24800	87.3065
23360	87.1602	23850	87.2143	24330	87.2581	24810	87.3064
23370	87.1605	23860	87.2155	24340	87.2594	24820	87.3075
23380	87.1622	23870	87.2167	24350	87.2609	24830	87.3094
23390	87.1636	23880	87.2186	24360	87.2631	24840	87.3106
23400	87.1645	23890	87.219	24370	87.2619	24850	87.3112
23410	87.1654	23900	87.2194	24380	87.2641	24860	87.312
23420	87.166	23910	87.2215	24390	87.2658	24870	87.3129
23430	87.1665	23920	87.222	24400	87.2671	24880	87.3147
23440	87.1674	23930	87.2221	24410	87.2684	24890	87.3158
23450	87.1684	23940	87.2232	24420	87.2682	24900	87.3143
23460	87.1695	23950	87.2238	24430	87.27	24910	87.3164
23470	87.1714	23960	87.2249	24440	87.2715	24920	87.318
23480	87.1727	23970	87.2253	24450	87.2731	24930	87.3186
23490	87.174	23980	87.2254	24460	87.2739	24940	87.3199
23500	87.1752	23990	87.2259	24470	87.2755	24950	87.3199
23510	87.1763	24000	87.2263	24480	87.2767	24960	87.3199
23520	87.1768	24010	87.2277	24490	87.2778	24970	87.3211
23530	87.1777	24020	87.2281	24500	87.2785	24980	87.3236
23540	87.1795	24030	87.229	24510	87.2798	24990	87.3239
23550	87.1813	24040	87.2302	24520	87.2791	25000	87.3247
23560	87.1817	24050	87.2319	24530	87.2803	25010	87.3262
23570	87.1824	24060	87.2327	24540	87.2814	25020	87.3272
23580	87.1847	24070	87.234	24550	87.2834	25030	87.3278
23590	87.1862	24080	87.2356	24560	87.284	25040	87.3276
23600	87.1875	24090	87.2371	24570	87.2848	25050	87.328

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
25070	87.3291	25560	87.3673	26040	87.3896	26520	87.4176
25080	87.3298	25570	87.368	26050	87.3914	26530	87.419
25090	87.3303	25580	87.3679	26060	87.3917	26540	87.4205
25100	87.3308	25590	87.3687	26070	87.393	26550	87.4213
25110	87.3314	25600	87.3686	26080	87.3932	26560	87.4204
25120	87.3311	25610	87.3682	26090	87.3939	26570	87.4195
25130	87.3324	25620	87.3671	26100	87.3943	26580	87.4182
25140	87.3334	25630	87.367	26110	87.3952	26590	87.4183
25150	87.3338	25640	87.3674	26120	87.3955	26600	87.4177
25160	87.3338	25650	87.3674	26130	87.3957	26610	87.4177
25170	87.3336	25660	87.3666	26140	87.3971	26620	87.4167
25180	87.3328	25670	87.3667	26150	87.3985	26630	87.4194
25190	87.3342	25680	87.367	26160	87.3993	26640	87.4287
25200	87.3351	25690	87.3678	26170	87.3995	26650	87.4486
25210	87.335	25700	87.3673	26180	87.3994	26660	87.4507
25220	87.3352	25710	87.3671	26190	87.4	26670	87.4513
25230	87.3352	25720	87.3682	26200	87.4002	26680	87.4521
25240	87.3355	25730	87.3696	26210	87.4005	26690	87.4517
25250	87.3355	25740	87.3694	26220	87.3998	26700	87.4516
25260	87.3355	25750	87.3704	26230	87.401	26710	87.4522
25270	87.3367	25760	87.3713	26240	87.402	26720	87.4522
25280	87.3375	25770	87.3716	26250	87.4028	26730	87.4521
25290	87.3368	25780	87.3717	26260	87.4051	26740	87.4517
25300	87.3537	25790	87.372	26270	87.4058	26750	87.4517
25310	87.3534	25800	87.3736	26280	87.4067	26760	87.4522
25320	87.3533	25810	87.3738	26290	87.409	26770	87.4531
25330	87.3529	25820	87.3744	26300	87.4096	26780	87.4547
25340	87.3523	25830	87.3756	26310	87.4096	26790	87.4548
25350	87.3535	25840	87.3752	26320	87.4103	26800	87.4557
25360	87.3509	25850	87.3763	26330	87.4113	26810	87.4562
25370	87.3518	25860	87.375	26340	87.4116	26820	87.4571
25380	87.3508	25870	87.3761	26350	87.4125	26830	87.4576
25390	87.3489	25880	87.3781	26360	87.4145	26840	87.4568
25400	87.3493	25890	87.3781	26370	87.416	26850	87.4571
25410	87.3476	25900	87.3786	26380	87.4164	26860	87.4573
25420	87.346	25910	87.3796	26390	87.4179	26870	87.4581
25430	87.345	25920	87.3802	26400	87.4184	26880	87.4583
25440	87.3442	25930	87.3806	26410	87.4174	26890	87.4583
25450	87.3586	25940	87.3813	26420	87.4178	26900	87.4585
25460	87.358	25950	87.3817	26430	87.4173	26910	87.4534
25470	87.3573	25960	87.3822	26440	87.4181	26920	87.4532
25480	87.356	25970	87.3836	26450	87.4174	26930	87.454
25490	87.359	25980	87.3839	26460	87.4181	26940	87.4536
25500	87.3631	25990	87.3849	26470	87.4174	26950	87.4543
25510	87.3641	26000	87.3871	26480	87.4187	26960	87.4572
25520	87.3636	26010	87.3874	26490	87.4195	26970	87.4567
25530	87.3649	26020	87.3872	26500	87.4187	26980	87.4585
25540	87.3652	26030	87.3891	26510	87.4179	26990	87.4589

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
27000	87.461	27490	87.5385	27970	87.5743	28450	87.5506
27010	87.4629	27500	87.5413	27980	87.5893	28460	87.5489
27020	87.4634	27510	87.5422	27990	87.5635	28470	87.5486
27030	87.4668	27520	87.5429	28000	87.5615	28480	87.5468
27040	87.4683	27530	87.5452	28010	87.5492	28490	87.5465
27050	87.4693	27540	87.5466	28020	87.5546	28500	87.5434
27060	87.4697	27550	87.5466	28030	87.5584	28510	87.5403
27070	87.4706	27560	87.5486	28040	87.5481	28520	87.5471
27080	87.4718	27570	87.5507	28050	87.5442	28530	87.5476
27090	87.4741	27580	87.5519	28060	87.5462	28540	87.5485
27100	87.4773	27590	87.5525	28070	87.5891	28550	87.5486
27110	87.4757	27600	87.5544	28080	87.5871	28560	87.5502
27120	87.4798	27610	87.5549	28090	87.5457	28570	87.5502
27130	87.4797	27620	87.5553	28100	87.5507	28580	87.5519
27140	87.4738	27630	87.5571	28110	87.5533	28590	87.5519
27150	87.4794	27640	87.5558	28120	87.5478	28600	87.5517
27160	87.4805	27650	87.5557	28130	87.5424	28610	87.5516
27170	87.4823	27660	87.556	28140	87.5568	28620	87.5528
27180	87.4842	27670	87.5586	28150	87.5447	28630	87.5529
27190	87.4845	27680	87.558	28160	87.5406	28640	87.5529
27200	87.4888	27690	87.5572	28170	87.5596	28650	87.5531
27210	87.4894	27700	87.5576	28180	87.5552	28660	87.5512
27220	87.4907	27710	87.5583	28190	87.5596	28670	87.5564
27230	87.492	27720	87.5599	28200	87.5541	28680	87.5534
27240	87.4937	27730	87.5576	28210	87.5587	28690	87.5676
27250	87.4904	27740	87.5559	28220	87.5575	28700	87.5767
27260	87.4919	27750	87.5527	28230	87.5509	28710	87.5542
27270	87.4909	27760	87.549	28240	87.5515	28720	87.5551
27280	87.4941	27770	87.5432	28250	87.5506	28730	87.5562
27290	87.4956	27780	87.5369	28260	87.5503	28740	87.5575
27300	87.497	27790	87.5292	28270	87.5526	28750	87.5562
27310	87.4999	27800	87.5182	28280	87.5516	28760	87.5564
27320	87.5014	27810	87.5104	28290	87.5534	28770	87.5535
27330	87.5058	27820	87.5046	28300	87.5537	28780	87.5533
27340	87.5043	27830	87.5049	28310	87.5529	28790	87.5499
27350	87.5098	27840	87.4985	28320	87.5519	28800	87.5495
27360	87.5123	27850	87.4868	28330	87.5508	28810	87.5489
27370	87.5117	27860	87.4763	28340	87.5506	28820	87.5488
27380	87.5147	27870	87.4675	28350	87.5489	28830	87.5479
27390	87.5251	27880	87.4617	28360	87.5487	28840	87.5476
27400	87.5315	27890	87.4544	28370	87.5499	28850	87.5469
27410	87.5335	27900	87.4484	28380	87.5535	28860	87.5478
27420	87.5345	27910	87.4433	28390	87.554	28870	87.5476
27430	87.5354	27920	87.4445	28400	87.5523	28880	87.5479
27440	87.5361	27930	87.484	28410	87.5514	28890	87.5485
27450	87.5355	27940	87.5523	28420	87.5516	28900	87.5498
27460	87.5359	27950	87.6229	28430	87.5528	28910	87.5492
27470	87.5367	27960	87.5874	28440	87.5516	28920	87.5514

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
27480	87.5366	29050	87.5515	29190	87.5451	29330	87.5248
28930	87.5512	29060	87.5504	29200	87.5455	29340	87.5245
28940	87.5516	29070	87.551	29210	87.5469	29350	87.5156
28950	87.5555	29080	87.5514	29220	87.5471	29360	87.5145
28960	87.5502	29090	87.5523	29230	87.5479	29370	87.5109
28970	87.5497	29100	87.5523	29240	87.5478	29380	87.52
28980	87.5489	29110	87.5567	29250	87.548	29390	87.5203
28990	87.5476	29120	87.5534	29260	87.5459	29400	87.5188
29000	87.5487	29130	87.55	29270	87.5406	29410	87.5188
29010	87.5499	29140	87.5459	29280	87.5412	29420	87.5232
29020	87.5513	29150	87.5455	29290	87.5433	29430	87.5199
29030	87.5521	29160	87.5468	29300	87.5423	29440	87.5236
29040	87.5519	29170	87.5613	29310	87.5468	29450	87.5234
29050	87.5515	29180	87.5442	29320	87.5359	29450	87.5234

Table 20: Sorption Isotherm Values from 75 to 85 % RH

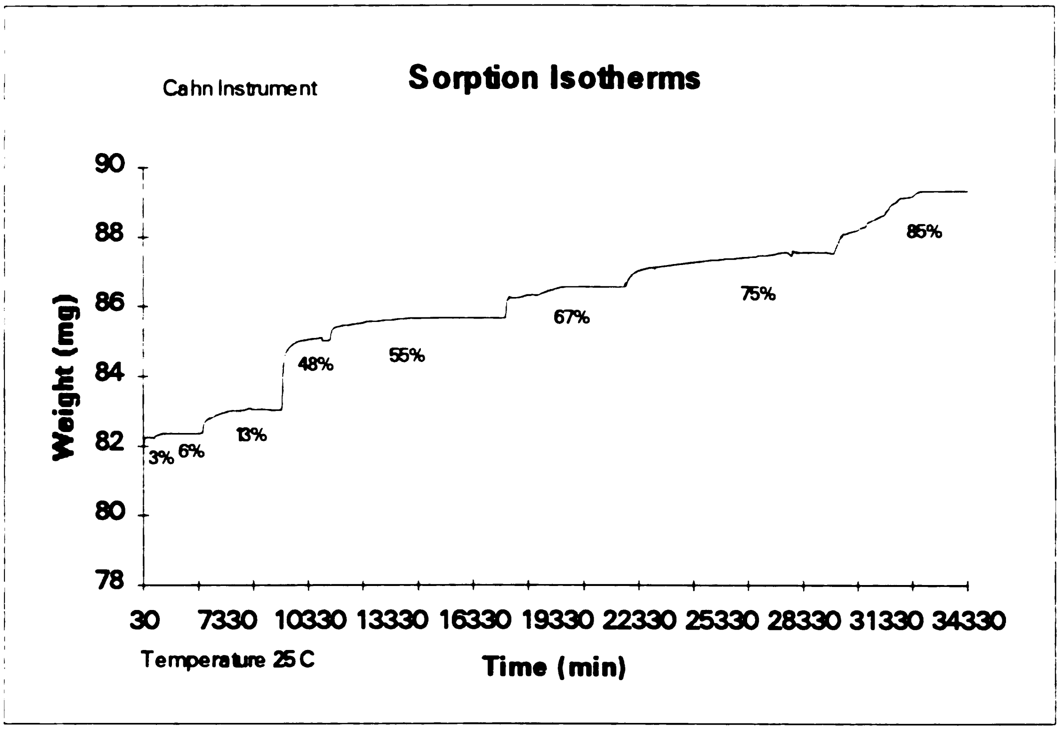
Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
29460	87.5407	29910	88.0881	30360	88.2067	30810	88.4586
29470	87.5625	29920	88.089	30370	88.2089	30820	88.4602
29480	87.5846	29930	88.095	30380	88.2275	30830	88.4656
29490	87.6062	29940	88.103	30390	88.2384	30840	88.4685
29500	87.6264	29950	88.108	30400	88.2497	30850	88.4697
29510	87.6463	29960	88.115	30410	88.2508	30860	88.4723
29520	87.6662	29970	88.125	30420	88.2555	30870	88.4768
29530	87.6864	29980	88.1267	30430	88.2587	30880	88.4776
29540	87.7039	29990	88.1269	30440	88.2604	30890	88.48
29550	87.7224	30000	88.1281	30450	88.2631	30900	88.4853
29560	87.7394	30010	88.1286	30460	88.2644	30910	88.49
29570	87.7571	30020	88.129	30470	88.2668	30920	88.4935
29580	87.7746	30030	88.1299	30480	88.2694	30930	88.4969
29590	87.7922	30040	88.1356	30490	88.2715	30940	88.5026
29600	87.811	30050	88.1386	30500	88.2734	30950	88.5039
29610	87.8294	30060	88.1394	30510	88.2756	30960	88.5086
29620	87.8464	30070	88.1427	30520	88.2768	30970	88.5105
29630	87.8659	30080	88.1466	30530	88.2787	30980	88.5113
29640	87.8855	30090	88.1489	30540	88.28	30990	88.5168
29650	87.9061	30100	88.1502	30550	88.2834	31000	88.5199
29660	87.9229	30110	88.155	30560	88.2848	31010	88.5223
29670	87.9423	30120	88.1576	30570	88.2864	31020	88.5368
29680	87.9611	30130	88.1586	30580	88.2897	31030	88.5391
29690	87.9787	30140	88.1594	30590	88.2912	31040	88.5468
29700	87.9973	30150	88.1606	30600	88.2934	31050	88.5503
29710	88.0123	30160	88.1616	30610	88.2954	31060	88.5565
29720	88.0282	30170	88.1643	30620	88.2967	31070	88.5591
29730	88.0415	30180	88.1675	30630	88.3541	31080	88.5628
29740	88.052	30190	88.1685	30640	88.3865	31090	88.5675
29750	87.9937	30200	88.1694	30650	88.3941	31100	88.5694
29760	88.052	30210	88.1705	30660	88.3987	31110	88.5734
29770	88.0735	30220	88.1728	30670	88.4012	31120	88.5745
29780	88.0828	30230	88.1765	30680	88.4039	31130	88.5782
29790	88.0829	30240	88.18	30690	88.4085	31140	88.5825
29800	88.0834	30250	88.1833	30700	88.4152	31150	88.5874
29810	88.0844	30260	88.1864	30710	88.4199	31160	88.5899
29820	88.0846	30270	88.1891	30720	88.4268	31170	88.5936
29830	88.0847	30280	88.1903	30730	88.43	31180	88.5982
29840	88.0853	30290	88.1909	30740	88.4368	31190	88.6014
29850	88.0856	30300	88.1925	30750	88.4389	31200	88.6053
29860	88.0858	30310	88.1945	30760	88.4401	31210	88.6079
29870	88.0864	30320	88.1968	30770	88.4425	31220	88.6107
29880	88.0868	30330	88.1999	30780	88.4468	31230	88.6155
29890	88.0872	30340	88.203	30790	88.4494	31240	88.6189
29900	88.0877	30350	88.2045	30800	88.4532	31250	88.6207

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
31260	88.6223	31750	89.0345	32230	89.1437	32710	89.3187
31270	88.6299	31760	89.0456	32240	89.1439	32720	89.3187
31280	88.6378	31770	89.0555	32250	89.1441	32730	89.3187
31290	88.6435	31780	89.0597	32260	89.1447	32740	89.3187
31300	88.6522	31790	89.0689	32270	89.1453	32750	89.3187
31310	88.6734	31800	89.0756	32280	89.1528	32760	89.3187
31320	88.6886	31810	89.0897	32290	89.1593	32770	89.3187
31330	88.6989	31820	89.0953	32300	89.1691	32780	89.3187
31340	88.7086	31830	89.0995	32310	89.1758	32790	89.3188
31350	88.7203	31840	89.1052	32320	89.1812	32800	89.3188
31360	88.7259	31850	89.1103	32330	89.1867	32810	89.3188
31370	88.7399	31860	89.1175	32340	89.1935	32820	89.3188
31380	88.7506	31870	89.1194	32350	89.1973	32830	89.3188
31390	88.7611	31880	89.1242	32360	89.2023	32840	89.3188
31400	88.7695	31890	89.1305	32370	89.208	32850	89.3188
31410	88.7777	31900	89.1309	32380	89.212	32860	89.3189
31420	88.7813	31910	89.1315	32390	89.2182	32870	89.3189
31430	88.7892	31920	89.13189	32400	89.2229	32880	89.3189
31440	88.7905	31930	89.1326	32410	89.2284	32890	89.3189
31450	88.7986	31940	89.133	32420	89.2345	32900	89.3189
31460	88.8781	31950	89.1335	32430	89.241	32910	89.3189
31470	88.8806	31960	89.1338	32440	89.2443	32920	89.3189
31480	88.8894	31970	89.1342	32450	89.2498	32930	89.319
31490	88.8902	31980	89.1345	32460	89.2563	32940	89.319
31500	88.8956	31990	89.1357	32470	89.2639	32950	89.319
31510	88.8995	32000	89.1364	32480	89.2698	32960	89.319
31520	88.9056	32010	89.1368	32490	89.2746	32970	89.319
31530	88.9154	32020	89.1374	32500	89.2786	32980	89.319
31540	88.9232	32030	89.1376	32510	89.2828	32990	89.3191
31550	88.9279	32040	89.1379	32520	89.2866	33000	89.3191
31560	88.9328	32050	89.1384	32530	89.2903	33010	89.3191
31570	88.9386	32060	89.1387	32540	89.2962	33020	89.3191
31580	88.9489	32070	89.1392	32550	89.2995	33030	89.3191
31590	88.9515	32080	89.1393	32560	89.3043	33040	89.3191
31600	88.9588	32090	89.1396	32570	89.31	33050	89.3191
31610	88.9623	32100	89.1399	32580	89.3126	33060	89.3191
31620	88.9666	32110	89.1402	32590	89.3149	33070	89.3191
31630	88.9746	32120	89.1406	32600	89.3181	33080	89.3192
31640	88.9778	32130	89.1411	32610	89.3182	33090	89.3192
31650	88.9806	32140	89.1415	32620	89.3183	33100	89.3192
31660	88.9868	32150	89.1417	32630	89.3184	33110	89.3192
31670	88.9897	32160	89.142	32640	89.3185	33120	89.3192
31680	88.9925	32170	89.1423	32650	89.3185	33130	89.3192
31690	88.9958	32180	89.1425	32660	89.3185	33140	89.3192
31700	88.9986	32190	89.1427	32670	89.3186	33150	89.3192
31710	89.0021	32200	89.143	32680	89.3186	33160	89.3192
31720	89.0102	32210	89.1432	32690	89.3186	33170	89.3192
31730	89.0187	32220	89.1435	32700	89.3186	33180	89.3192

Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)	Time (min)	Weight (g)
33190	89.3192	33490	89.319	33800	89.3195	34100	89.321
33200	89.3192	33500	89.319	33810	89.3194	34110	89.321
33210	89.3193	33510	89.319	33820	89.3198	34120	89.321
33220	89.3193	33520	89.319	33830	89.3199	34130	89.321
33230	89.3193	33530	89.3189	33840	89.3199	34140	89.321
33240	89.3193	33540	89.3189	33850	89.3199	34150	89.321
33250	89.3193	33550	89.3189	33860	89.32	34160	89.321
33260	89.3193	33560	89.3189	33870	89.32	34170	89.321
33270	89.3193	33570	89.3189	33880	89.32	34180	89.321
33280	89.3193	33580	89.3188	33890	89.32	34190	89.321
33290	89.3193	33590	89.3188	33900	89.32	34200	89.321
33300	89.3192	33600	89.3188	33910	89.32	34210	89.321
33310	89.3192	33610	89.3188	33920	89.32	34220	89.321
33320	89.3192	33620	89.3188	33930	89.32	34230	89.321
33330	89.3192	33630	89.3188	33940	89.32	34290	89.321
33340	89.3192	33640	89.3188	33950	89.32	34300	89.321
33350	89.3192	33650	89.3187	33960	89.32	34310	89.321
33360	89.3192	33660	89.3187	33970	89.32	34320	89.321
33370	89.3192	33680	89.3189	33980	89.32	34330	89.321
33380	89.3192	33690	89.319	33990	89.32	34340	89.321
33390	89.3191	33700	89.319	34000	89.32	34350	89.321
33400	89.3191	33710	89.3191	34010	89.32	34360	89.321
33410	89.3191	33720	89.3193	34020	89.32	34370	89.321
33420	89.3191	33730	89.319	34030	89.32	34380	89.321
33430	89.3191	33740	89.3187	34040	89.32	34380	89.321
33440	89.319	33750	89.3188	34050	89.32	34380	89.321
33450	89.319	33760	89.3185	34060	89.32	34380	89.321
33460	89.319	33770	89.3188	34070	89.321	34380	89.321
33470	89.319	33780	89.3189	34080	89.321	34380	89.321
33480	89.319	33790	89.319	34090	89.321	34380	89.321

APPENDIX F

Plot of The sorption Isotherms Values
under Various Humidities tested by Cahn Electrobalance



BIBLIOGRAPHY

Anonymous, "Guide to Plastics", *Modern Plastic*, Hill Mcgraw, NY., 1987, pp. 57

Baer, Eric, "Thermal Stability", *Engineering Design for Plastics,* Polymer and Engineering Series, 1964, pp. 401-403.

Baner, A.L.(III); Hernandez, R.J.; Krishnamurthy, J.; Giacin, J.R., "Isostatic and Quasi-Isostatic Methods for Determining the Permeability of Organic Vapors Through Barrier Membranes." *Current Technologies in Flexible Packaging, ASTM STP 912,* M.L. Troedel, Ed., American Society for Testing and Materials, Philadelphia, 1986, 49-62.

Blatz, Philip S., E.I. duPONT de NEMOURS & Co., Inc., " Properties of Film From Blends of Amorphous and Crystalline Nylons", *Innovationsin Polyamide Technology, Aiche Meeting,* April 2-6, 1989, Houston, Texas.

Blatz, Philip S., E.I. duPONT de NEMOURS & Co., Inc., "Next Generation of Barrier Packaging Resins", *Selar ® PA High Barrier Nylons, Polymeric Packaging Materials Reading,* School of Packaging, Michigan State University, Fall 1992.

Briston, J.H. "Films, Plastics." *The Wiley Encyclopedia of Packaging Technology,* 1986, pp.330.

Bradrup, J., and Immergut, E.H, Ed., *Polymer Hand Book,* interscience, New York, 1991.

Boyer(ed), "Encyclopedia of Polymer Science and Technology, Supplement no.2", Wiley & Sons, N.Y., 1977.

Cambell, G.A., *J.Polymer Science,* 1969, 7B, pp.629.

Casale, A.S., and Porter, R.S., *Rubber Chemical Technology,* 1971,(44), pp.534

Clark, E.S. and Wilson, F.C., "Nylon Plastics" John Wily & Sons Inc, N.Y., 1973.

Crank, J. "The Definition and Measurement of Diffusion Coefficients." *The Mathematics of Diffusion,* 2nd edition, 1975, 238-239.

Crank, J. and Park, "Diffusion In Polymers". Academic Press, N.Y. 1968.

Gavara R. and Hernandez R.J., "Binmodal Diffusion Process in thhe Oxygen Mass Trasport through Nylon 6 at Different Temperature and Water Activity Conditions", *Processing of the American Society for Composites,* October 13-15, 1992, Keller Conference Center, University Park, Pennsylvania.

Hernandez, R.J., J.R. Giacin and A.L. Baner, "The Evaluation of the Aroma Barrier Properties of Polymer Films", *J. Plastic Film Sheeting*, 1986, 2, 187-211.

Hernandez, R.J., J.R. Giacin and E.A. Gruke, "The Sorption of Water Vapor by an Amorphous Polyamide", *J. Membrane Science (in press)*, 1991.

Hernandez, R.J., "Effect of water vapor on the transport properties of oxygen through polyamide packaging materials.", Fifth international symposium on properties of water, November 8-14, 1992, Valencia, SPAIN.

Hopfenberg, H.B., and stannet, V., 1973 " The Physics of Glassy Polymers", R.N. Haward(ed), ch9, *The Diffusion and Sorption of Gases and Vapors in Glassy Polymners,* Applied Science Publishers LTD, London.

Imbalzano, J.F.; Washburn, D. N. ; Mehta, P.M. "Permeation and Stress cracking of Fluropolymers." *Chemical Engineering,* January 1991, 105-108.

Kohan, Melvin.I. *Nylon Plastics,* Plastics Department, E.I. du Pont de Nemours and Co., Inc.

Langmuir, I., J., American Chemistry and Society. 1918, 40, 1361.

Lebovits, A., "Permeability of Polymers to Gases", Vapors and Liquids, *Modern Plastics,* 1966, (43), pp.139.

Mark, F. Herman, John Wiley and Sons Inc. "Polyamides", *Encyclopedia of Polymer Science and Technology,* 1969, (10), pp.553-545.

Mason, A., John and Sperling H. Leslie. "General Behavior of Polymer Mixtures." *Polymer Blends and Composites,* 1976, pp.52-53.

Matsuo, M., " Thermal Analysis", *Japan Plastics,* 1968, (2), July, 6.

Meares, P., "Polymers: Structure and Bulk Properties", Van Nostrand & Co.Ltd, London

Nielson, Lawrence E., *Mechanical Properties of Polymers and composites,* Vol.1 Marcel Dekker Publishing co., 1974.

Ohashi, Kuniyoshi, "Modeling the Sorption of Water Vapor by a Semicrystalline of Polyamide Application of a New Interpretative Sorption Model", Thesis for the Degree of M.S., Michigan State University, 1991.

Olabisi, Olagoke; Robeson, lloyd M.; and Shaw, Montgomery T., "Methods of Determining Polymer-Polymer Misibility", *Polymer-Polymer Miscibility,* 1979, charpter 3, 117-174.

Robertson, G.L. "Structure Properties of Plastic polymers", *Food Packaging: Principal and Practice,* 1992, Chapter 2, 31-48.

Rodriguez Ferdinand, Professor of chemical engineering, Cornell University, "Polyamides and related polymers", *Principle of Polymer System,* 1982, 449-467.

Satton, W.O., *J.Polymer Science,* 1967, 18C, pp.33.

Seymour B. Raymon, "Aliphatic and Aromatic Polyamides (Nylons)", *Engineering Polymer Source book,* McGraw-Hill Publishing Company, 1990, pp. 179-188

Stannett, V.; Yasuda H. "The Measurement of Gas and Vapor Permeation and Diffusion in Polymer.", *Testing of Polymers,* 1965, Volume 1, Charpter 13, John Wiley and Sons, Inc.

Starkweather, H.W., "Nylon Plastics"., John Wiley & Sons, N.Y. 1973

Tubridy, M.F.; Sibilia, J.P. "Nylon." *The Wily Encyclopedia of packaging Technology,* 1986, 477-482

Wunderlich, B., and Cromier, *J. Polymer Science,* 1967., A-2, 5, pp.987.