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## Poly(ether imide)s: Synthesis and Properties

Rachel Price

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Murray State University Honors College

HONORS THESIS

Certificate of Approval

**Poly(ether imide)s: Synthesis and Properties**

Rachel Price

Graduation Date: May 13, 2023

Approved to fulfill the  
requirements of HON 438

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Dr. Kevin M. Miller, Professor  
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Approved to fulfill the  
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of the Murray State Honors  
Diploma

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**Poly(ether imide)s: Synthesis and Properties**

Submitted in partial fulfillment  
of the requirements  
for the Murray State University Honors Diploma

Rachel Price

Completion Date: April 17, 2023

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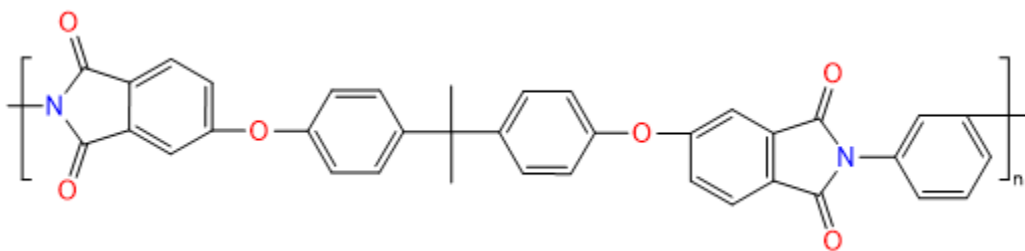
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## Poly (ether imide)s: Synthesis and Properties

Polyimides were developed and marketed for their high temperature resistance, high strength in comparison to weight, for example a relatively light object being very strong, and their mechanical properties. Poly(ether imide)s (PEIs), were produced to counter the properties of polyimides by the incorporation of bisphenol a diether dianhydride (BPADA), and the addition of an isopropylidene linkage, enhancing their solubility and therefore their processability (**Figure 1**). In 1982, GE Plastics invented the first poly(ether imide), trademarked as ULTEM Resin. PEIs also feature electrical insulation properties, flame resistance, and desirable chemical resistance.<sup>1</sup>



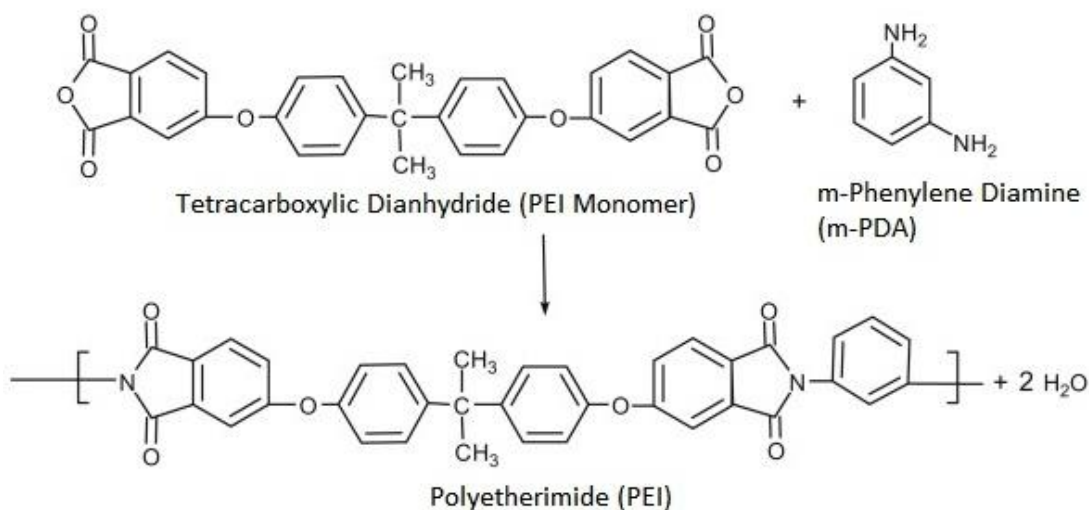
**Figure 1:** PEI with 4,4' BPADA.

One of the disadvantages to PEIs is their low customizability in terms of color, as PEIs are currently a translucent yellow, or in some cases dark brown, a difficult color to dye into other colors, which is also a challenge to polyimides. This color comes from charge transfer complexes that result from the  $\pi$ -stacking of the highly conjugated PEIs. They are also expensive and are mostly used in demanding applications that require high-performance polymers and are not conveniently melt processible. PEIs are commonly used in aerospace for their high heat resistance and flame retardancy, the automotive industry for their metalizing properties for headlights, food service for their steam resistance for cleaning and sterilization, and medical service for sterilization because of their chemical and UV resistance to detergents and UV disinfection. PEIs are also used in technology such as phones and computers for their electrical insulation. For ULTEM™ resins,

there are different varieties commercialized, including 4 grades of glass filled versions which can help replicate glass and strengthen the polymer, which naturally increases the price.<sup>2</sup> Their applications are numerous; however, because of their high cost they are used in small parts like headlights rather than larger products like bumpers, which typically use polycarbonate instead. Other groups improving upon specific characteristics of the PEI will be covered in this thesis, but the improvement of one quality usually means the decline in another.

PEIs are made through a polycondensation reaction, which is a reaction consisting of two or more monomers, each containing one or more functional groups, which in this case are a dianhydride and a diamine, that are combined in such a way to result in the loss of a smaller molecule, such as water as shown in **Figure 2**, but could be a different gas in other cases.<sup>3</sup> For PEIs, the reaction first starts with nucleophilic acyl attack by one of the amino groups of the diamine to the carbonyl of the dianhydride species forming an amic acid derivative. This reaction repeats in a step-growth fashion to produce a polyamic acid species while generating water. The final step is an intramolecular cyclodehydration reaction converting amic acid moieties into imides, producing the poly(ether imide).<sup>4</sup>



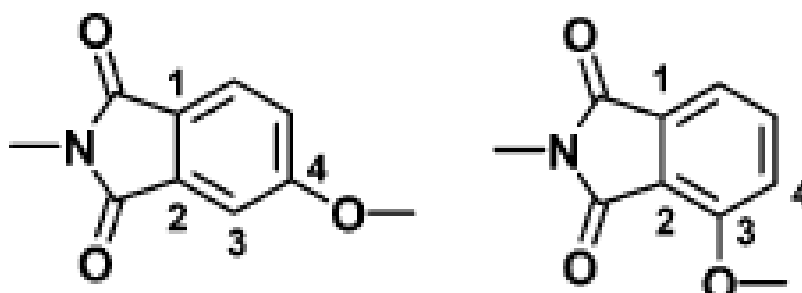


**Figure 2:** Synthesis of PEI between bisphenol-A phthalanhydride and a diamine.<sup>1</sup>

As the methods used to create PEIs all require solvents, a major hinderance in the process is the removal of the water from the reaction, as the solvent and the water must all be removed before post-processing. Getting solvent and water out separately is easier, as the solvent or water could evaporate out. However, with two different boiling points, finding an efficient separation method can be challenging and is the prime source of the high price tag.<sup>2</sup>

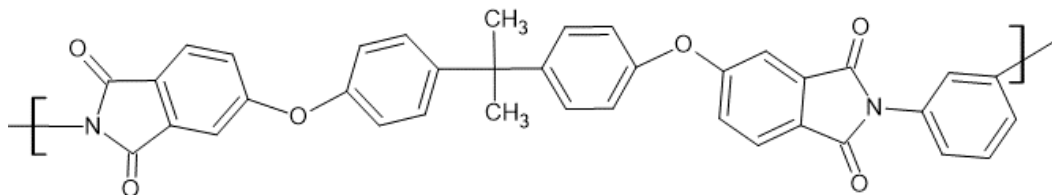
PEIs are a broad category of high-performance polymers, and the polymer can be adjusted on the molecular scale to provide different properties depending on the application the polymer will be used for. Many different monomers are compatible with making PEIs, so there are many combinations to be made. Some commonly sought-after properties are chain stiffness, the interactions between multiple chains to create strong bonds, flame retardancy, and solubility. Within these monomers, further tuning can be done through isomerization. These isomers are named by the placement of the ether linkage relative to the imide. IUPAC convention says the imide group is the first priority and to start at the farthest point of the group and continue through

to the second priority group, namely the oxygen. **Figure 3** shows this rule pictorially and is shown counting counterclockwise.<sup>5</sup>



**Figure 3:** Counting System and Structures of PEIs.<sup>5</sup>

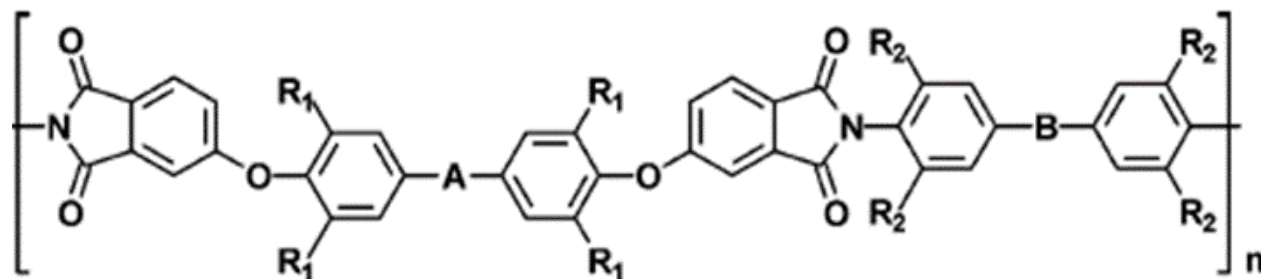
PEIs made with 3,3'-BPADA (3,3'-PEI) are where the oxygen molecule is connected *meta* to the first position of the phthalimide of the repeating group as shown in **Figure 4**.



**Figure 4:** PEI with 3,3' BPADA.

PEIs made with 4,4'-BPADA (4,4'-PEI) are analogous to 3,3'-PEI, but the oxygen is connected *para* to the first position of the phthalimide (**Figure 5**). Additionally, bulky groups also can have a large effect on the properties. For example, in **Figure 5**, having R1 or R2 be hydrogen or methyl groups can have a noticeable effect on the glass transition temperature ( $T_g$ ), the temperature at which the material transitions from a glassy state into a rubbery or syrupy consistency, and the

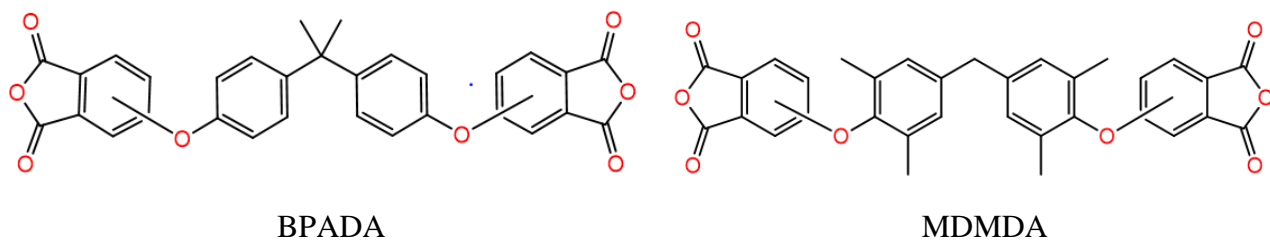
permeability which is the ability of a substance to penetrate through a polymer without physically or chemically affecting the polymer.<sup>5</sup>



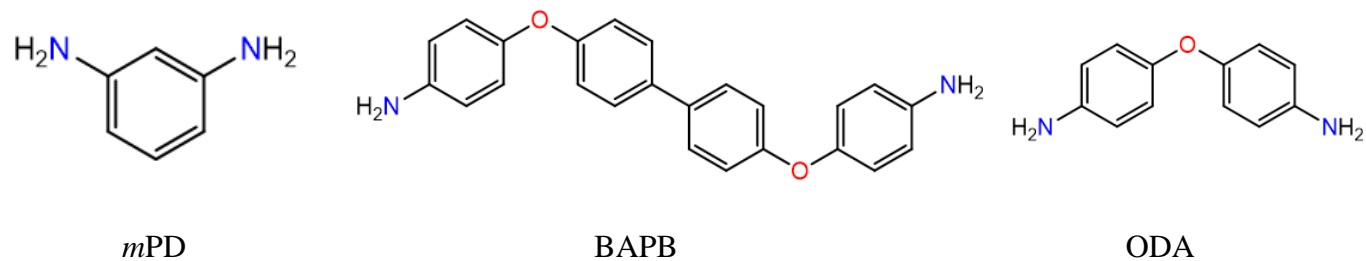
**Figure 5:** Model of *ortho*-substituents placement locations on PEI.<sup>5</sup>

Eastmond *et al.* found that replacing  $R_1$  or  $R_2$  (**Figure 5**) with a methyl group raised the  $T_g$  of the PEI as well as its permeability ( $M_p$ ). Replacing both  $R_1$  and  $R_2$  with methyl groups was shown to raise the effect on  $T_g$  and permeability even more. This study also showed that replacing  $R_1$  with methyl groups and maintaining  $R_2$  as hydrogen atoms seemed to have a greater effect than the inverse. This effect is related to the loss of freedom by reducing the polymer's ability to rotate about the ether linkage, while replacing  $R_2$  would simply reduce the maneuverability about a rigid rotor.<sup>6</sup>

PEIs composed of either 3,3'- or 4,4'-linked phthalimide, are constitutionally the same, but they have different characteristics. According to Eastmond *et al.* for 3,3'-PEI, the  $T_g$  is on average slightly higher than that of 4,4'-PEI, however the differences are not very extreme. Depending on the rigidity of the structure, you can get even more differences, like a higher permeability in the 4,4' PEI.<sup>5</sup>



**Figure 6:** Structure of bisphenol A dianhydride (BPADA) and methylenebis(2,6-methyldianhydride) (MDMDA).



**Figure 7:** Structures of *meta*-phenylene diamine (*m*PD), bis(4-aminophenoxy)biphenyl (BAPB), oxydiamiline (ODA).<sup>5</sup>

**Table 1:** Excerpt from Poly(ether imide)s Prepared from Bis(ether anhydride)s. All polymers have molecular weights of >60 kDa.  $M_p$  is the permeability of carbon dioxide.<sup>5,7</sup>

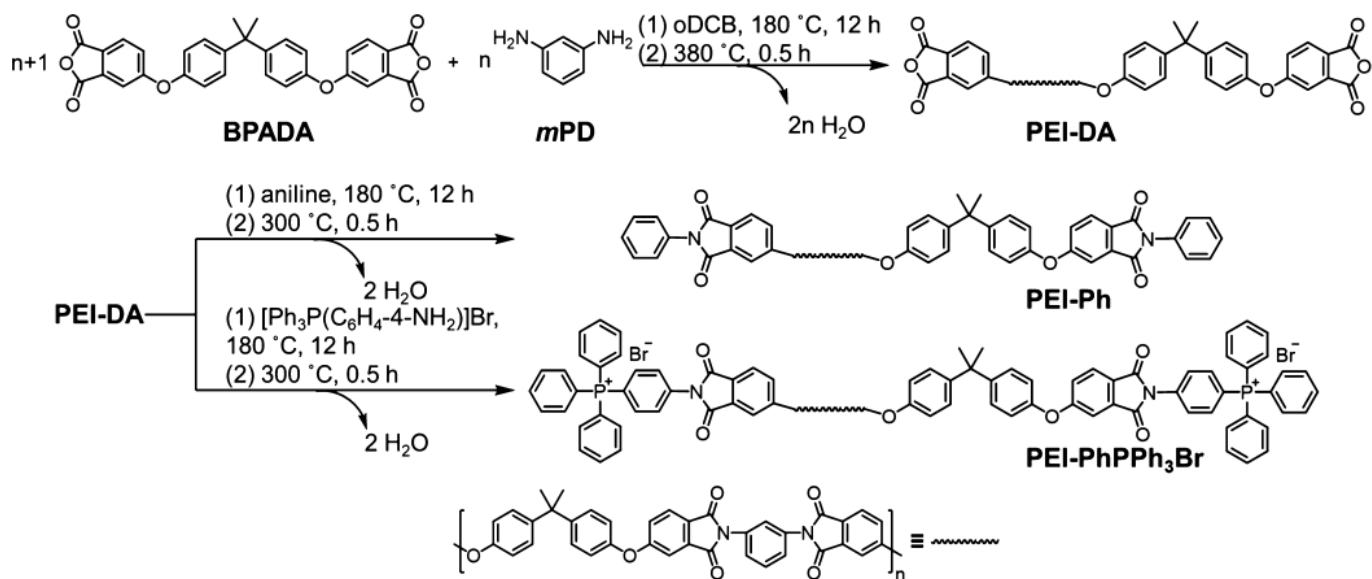
Dianhydride	Diamine	Substitution	$T_g$ (°C)	$M_p$ (kg·mol <sup>-1</sup> )
BPADA	ODA	3-	231	28
BPADA	ODA	4-	215	90
BPADA	<i>m</i> PD	3-	219	7.7
BPADA	<i>m</i> PD	4-	215	1.4 <sup>8</sup>
BPADA	BAPB	3-	236	106
BPADA	BAPB	4-	220	130
MDMDA	<i>m</i> PD	3-	269	11.8
MDMDA	<i>m</i> PD	4-	245	66
MDMDA	BAPB	3-	259	94
MDMDA	BAPB	4-	248	

3,3'-PEI was also shown to have a lower thermo-oxidative stability, which is the polymer's ability to maintain its mechanical properties, such as strength and elasticity, as temperature increases. As shown in **Figures 6 and 7**, a PEI made with 3,3'-BPADA and ODA was shown to have a  $T_g$  of 231°C and a permeability of 28 kg·mol<sup>-1</sup> of carbon dioxide. Compared to its counterpart, 4,4'-PEI was shown to have a  $T_g$  of 215°C, which is significantly lower. This is a result of the 3-isomer inhibiting rotation around the ether linkages, enhancing its rigidity, and therefore increasing its  $T_g$  relative to the 4,4'-isomer. Though the 3,3'-PEI has a higher  $T_g$ , its permeability is lower (28 kg·mol<sup>-1</sup>) than the 4,4'-PEI, which has a permeability of 90 kg·mol<sup>-1</sup>. Similar results are shown with the PEI made from BPADA and *m*PD, with the 3,3'-PEI having a  $T_g$  of 219°C and a permeability of 7.7 kg·mol<sup>-1</sup>, and the 4,4'-PEI of the same monomers having a  $T_g$  of 215°C and a permeability of 1.4 kg·mol<sup>-1</sup>. This can also be seen in PEI made with BPADA and BAPB, with the 3-isomer having a  $T_g$  of 236°C compared to the 4-isomer's  $T_g$  of 220°C. The results indicated that the 3-isomer had a 106 kg·mol<sup>-1</sup> permeability and the 4-isomer having a permeability of 130 kg·mol<sup>-1</sup>. Similar results are shown with PEIs made with MDMDA as the dianhydride. The combination of MDMDA and *m*PD showed the 3-isomer having a  $T_g$  of 269°C

and the 4-isomer having a  $T_g$  of 245°C. The permeabilities of each are 11.8 kg·mol<sup>-1</sup> for the 3-isomer and 66 kg·mol<sup>-1</sup> for the 4-isomer. MDMDA and BAPB showed a 3-isomer  $T_g$  of 259°C and a 4-isomer  $T_g$  of 248°C. Their permeabilities are 94 kg·mol<sup>-1</sup> for the 3-isomer, and no permeability value was listed for the 4-isomer. This data shows a trend in  $T_g$ , as the  $T_g$  of PEIs with the 3-isomer have a  $T_g$  around 10-20°C lower than that of the 4-isomer. Permeability shows a slight increase in the 4-isomer, but little trend appears. Overall, as the  $T_g$  decreases, the permeability increases, which could be in part due to the wider range of temperatures the polymer can go through in an amorphous state that can increase permeability as temperature rises.<sup>5</sup>

Cao *et al.* did a study on improving flame retardancy, which is very important for the public in the field of aeronautics because it makes sure that if an aircraft engine catches fire, the aircraft itself will not and keep the passengers safe.<sup>8</sup> Their concept was terminating the PEI with phosphonium bromide to end with a polymer with high mechanical properties, thermal stability, and flame retardancy. It is important to note that many of these polymers are created in response to customer needs. One property is not greater than another, but to meet the customer's future use, different properties become more important over others. The phosphonium group (tetraphenylphosphonium) was chosen due to its large phenyl group that provides steric hinderance

and prevents decomposition. The reaction used to create the PEI with phosphonium end caps is shown in **Figure 8**.<sup>8</sup>



**Figure 8:** Reaction used to synthesis a PEI with a phosphonium end cap.<sup>8</sup>

These polymers were tested for their flame retardancy using UL-94 ratings, which is a standard rating assigned according to how long they burn in different orientations. There are 6 ratings that can be assigned, but all the materials tested in **Table 2** received a V-0 rating which is defined as “Burning stops within 10 seconds on a vertical part allowing for drops of plastic that are not” in flames.<sup>9</sup>

**Table 2:** Flame retardancy data for PEIs terminated in a phenyl group, the phosphonium bromide group, and two reference PEIs, respectively.<sup>8</sup>

sample ( $M_n$ )	LOI (%)	UL-94 grade	dripping (Y/N)
PEI-Ph (12k)	44.5 ± 0.5	V-0	N
PEI-PhPP <sub>3</sub> Br (12k)	51.0 ± 0.5	V-0	N
PEI-1 (16.9k)	42.0 ± 0.5	V-0	Y
PEI-2 (24.5k)	45.0 ± 0.5	V-0	Y

The most notable feature of the data in **Table 2** is the dripping column. This was used to reflect the liquification of the polymer in response to the heat introduced. If an airplane were to crash, the company would not want it to melt, so this is an important feature. Dripping was evaluated on a yes or no basis, saying whether or not drops of liquid polymer dripped off the sample while in contact with flame. As detailed above, only the reference polymers showed signs of dripping, proving the validity of the group's hypothesis of adding the phosphonium group to the flame-retardant material. The tests summarized in **Table 2** was performed at 320°C for each polymer.<sup>8</sup>

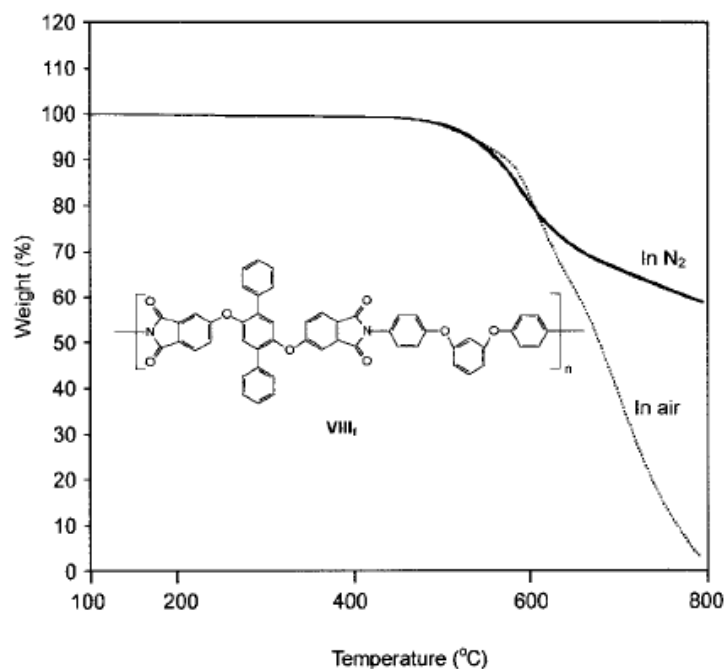
Included in **Table 2** are LOI values for each polymer, which stands for the limiting oxygen index, which is the percentage by volume of oxygen required in an oxygen and nitrogen rich air required to keep a flame burning. The higher the value, the more oxygen is required, and the more likely a flame will go out. The phosphonium terminated PEI has an LOI of approximately 51%, showing that it requires about an equal amount of oxygen and nitrogen in the air to keep a flame burning on that material. The atmosphere around Earth is approximately 21% oxygen and 79% nitrogen, which means if this polymer were to catch on fire in open air, it wouldn't last very long. The  $T_g$  of the phosphonium PEI was also higher than the phenyl terminated polymer as shown by DSC, differential scanning calorimetry, and also exhibited the best shear-thinning properties out of any of the tested polymers, meaning that it has the ability to become less viscous while keeping its mechanical properties, making it a good option in terms of melt processibility as discussed previously. The presented polymer had a molecular weight of 12 kDa, which surprised the group since this is a relatively low molecular weight for these types of characteristics to show up. For this study, Cao *et al.* plan to make improvements to the phosphonium terminated PEI to make it



more applicable to the fields of water treatment by using them to create polyelectrolytes and also using the PEI to make antimicrobial coatings.<sup>8</sup>

Due to their aromatic structure, which produces strong  $\pi$ - $\pi$  stacking between polymer chains, PEIs have low solubility and therefore are limited to polar, aprotic solvents like dimethyl sulfoxide (DMSO), *N*-methyl-2-pyrrolidone (NMP), or *N,N*-dimethylacetamide (DMAc).<sup>2,10</sup> In adapting to this, the idea was raised that adding ether groups to the backbone of the polymer can improve the solubility. The disadvantage of this approach is that ether groups generally decrease the  $T_g$  through improved backbone flexibility. To overcome this, large side groups can increase  $T_g$ . In addition, bulky groups on the backbone increase the solubility as shown by Hsiao et al. with *tert*-butyl and phenyl groups.<sup>10</sup>

Thermal gravitational analysis, (TGA), was used to show that the molecular weight remains steady up around 550°C, and then decreases significantly moving forward (**Figure 9**).<sup>10</sup> These results show the high thermostability of PEIs in both nitrogen and in air, making them good for high heat operations and most likely keep them flame retardant.

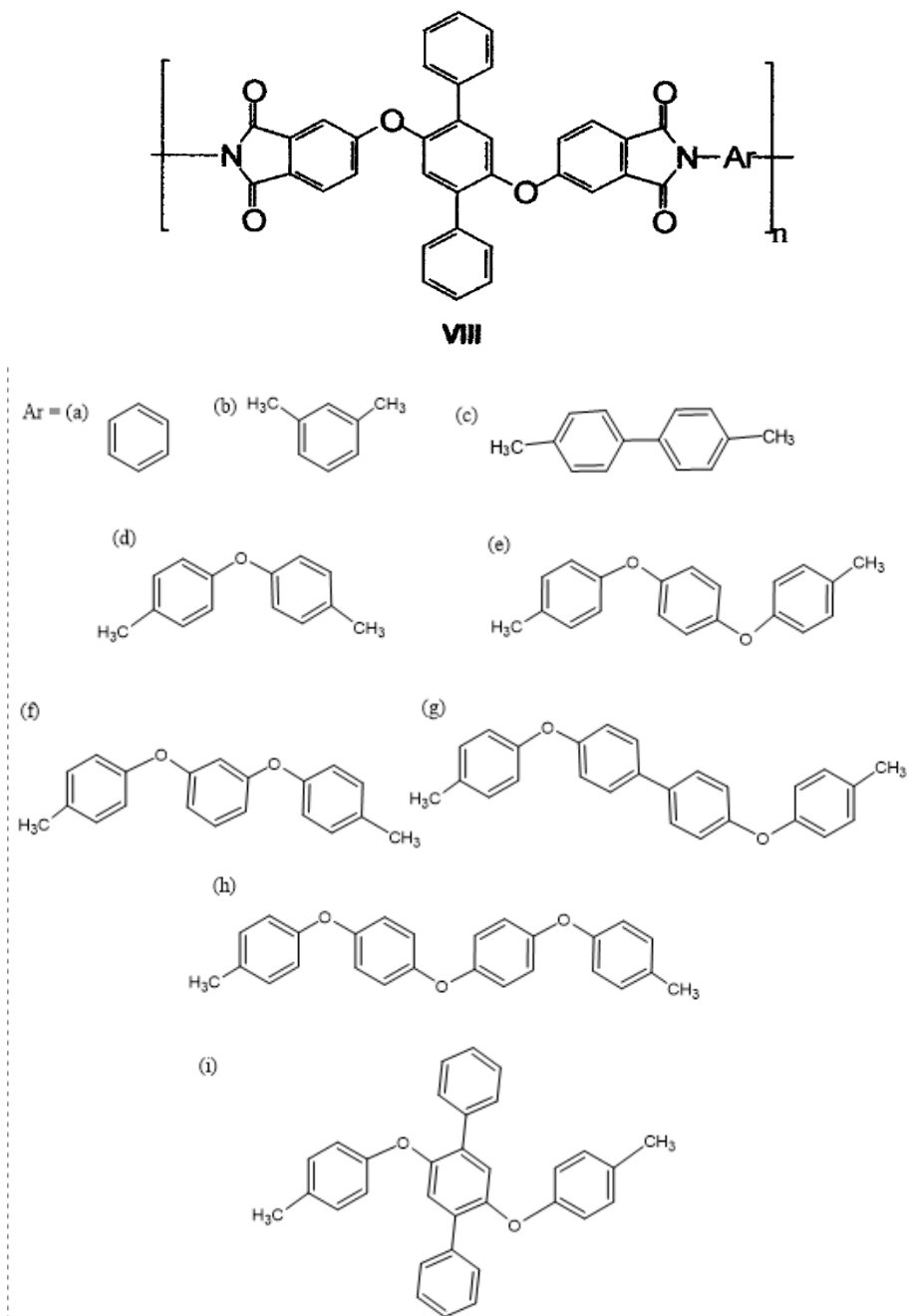


**Figure 9:** TGA thermogram of poly(ether imide) at a heating rate of 20 °C/min.<sup>10</sup>

Within the study by Hsiao *et al.*, PEIs were observed qualitatively for their solubility, and found the number of successfully soluble solutions had increased (**Figure 10**). It was found that two of their PEIs were soluble in aprotic, polar solvents like NMP, DMAc, and DMSO, while four of the trials were soluble in not only the aprotic, polar solvents, but also chlorinated solvents such as 2-chlorophenol and chloroform, which gives many options for solvents that can be used. These PEIs were tested for their tensile strength as well, with all being able to be pressed into films and showing strengths of 71-129 MPa as shown in **Table 3**.<sup>10</sup>

**Table 3:** Tensile Properties of Poly(ether imide) Films.<sup>10</sup>

Polymer Code	Strength at Break Point (MPa)	Elongation at Break Point (%)	Initial Modulus (GPa)
VIII <sub>a</sub>	129	15	2.17
VIII <sub>b</sub>	71	10	1.71
VIII <sub>c</sub>	122	14	2.06
VIII <sub>d</sub>	123	17	2.06
VIII <sub>e</sub>	90	16	1.92
VIII <sub>f</sub>	95	16	2.09
VIII <sub>g</sub>	111	35	1.90
VIII <sub>h</sub>	107	14	1.83
VIII <sub>i</sub>	103	13	1.97

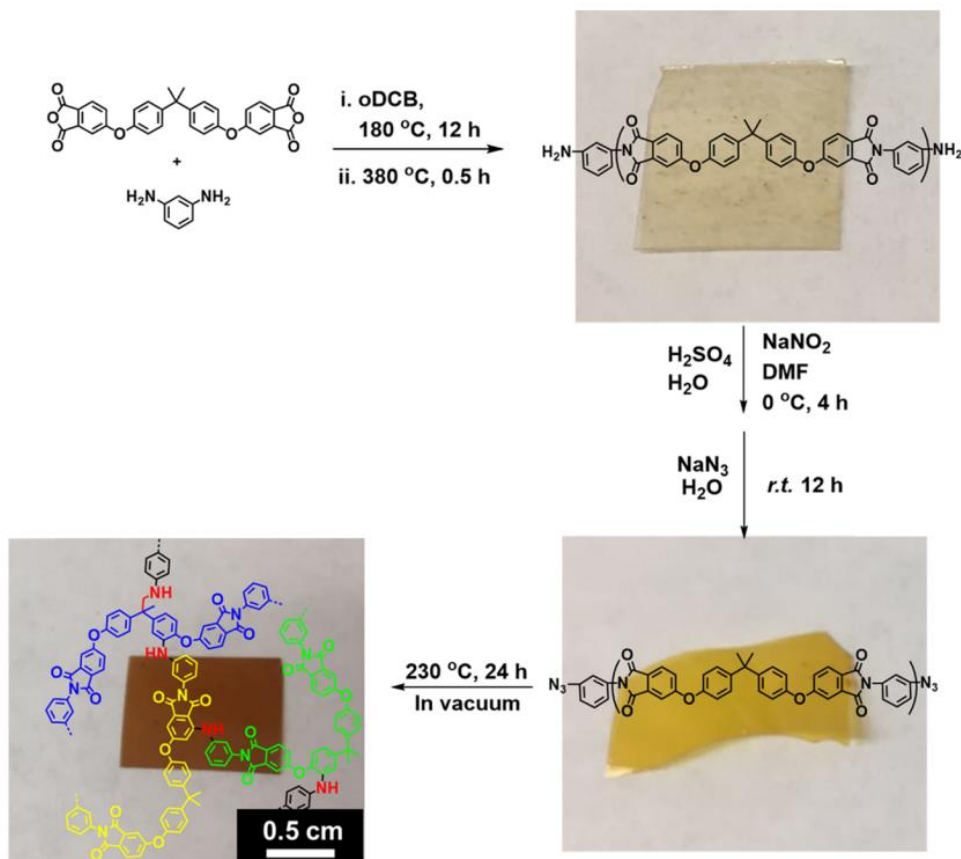


**Figure 10:** Structure of PEI tested by Hsiao et al.<sup>10</sup>

**Table 3** shows the tensile strengths of films at their break points as well as the percent elongation before breaking and the initial modulus, which is the ratio of stress and strain of the polymer before breaking. The polymers used in **Table 3** are shown in **Figure 10**, with the polymer labelled VIII being the base, and the label Ar on the left of the polymer is varied with the end caps

labelled with letters a through i. It can be inferred that the para connection is preferred over the meta attachments as seen in the results for linker b being much lower than the others. Linkers d through g most likely have the longest elongation due to their chain length being in a sweet spot of being a relatively long chain without having potential steric or rotational issues, which is most likely the issues with h and i. Linker a is most likely a strong backbone because it is shorter and leaves room for internal interactions between oxygen and nitrogen atoms.<sup>10</sup>

Solvent resistance can be a good property to have as scientists for cleaning or test purposes, but a customer would not want a polymer dissolving in the middle of use. PEIs are known to swell or dissolve in their known solvents, like THF and DCM, which is never a good thing to have happen. Work done by Xu *et al.* studied the use of ultraviolet light and thermal crosslinking to enhance the solvent resistance of the polymer.<sup>11</sup> The polymers were end capped by azides as azides have the highest crosslinking efficiency with the least amount of risk for explosion or linker leaching, which is the loss of part of the linker being taken by the solvent and not kept in the polymer. To create the azide end cap, the group used a heterogenous diazotization-azidation reaction. The crosslinking of the polymer is performed through thermolysis at what the group calls a “moderate temperature” and produces nitrenes, aziridines, and dehydroazepine that are highly reactive with groups such as amine, azide, aryl, and alkyl in PEI. The synthesis of the polymer is shown in **Figure 11**.<sup>11</sup>

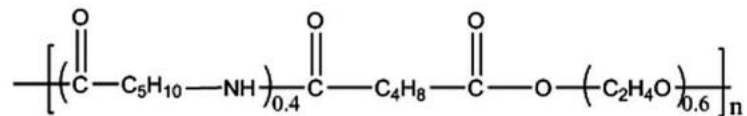


**Figure 11:** Synthesis of azide terminated PEI taken from Xu et al.<sup>11</sup>

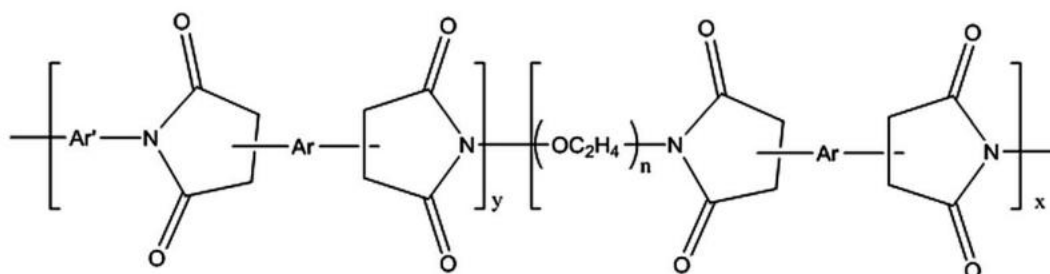
Films were then pressed and crosslinked afterwards. The resulting polymers showed exemplary resistance to traditional solvents like THF and DCM and even lasted for an hour in these solvents at 150° C without dissolving, swelling, or leaching. As PEIs were known to swell even in less radical conditions, this was a large breakthrough for this study. Uncrosslinked polymers dissolved readily into the solvents, so it was determined that crosslinking was the cause of the improved solvent resistance. In addition to the improved solvent resistance, the polymers also had improved  $T_g$  and storage moduli values in comparison to the reference group, which was Ultem 1010, a higher molecular weight PEI.<sup>11</sup> Having a resistance to solvents can be good for polymers in the post processing as they will be less likely to break down in use, but in

preprocessing it is important to have a lower solvent resistance so that the polymer can flow through pipes and be tested on the various instruments.

One of the most common discussions within the chemical field is the use of green chemistry. When it comes to polymers, most people think about the biodegradability of the polymer, but there are more factors to keeping the Earth clean, like the release of carbon dioxide into the atmosphere within a chemical process. A study by Tena *et al.* investigated the use of PEIs as a kind of filter to capture harmful gases, like carbon dioxide and methane, and let the inert gases back into the atmosphere.<sup>12</sup> The goal of this study was to compare their poly(ether amide) to a poly(ether imide) and see which was better at filtering out harmful gases and filtering out the inert gases, like nitrogen and oxygen. PEIs made with poly(ether oxides), or PEOs, seemed to have the best selectivity for filtering out the harmful gases due to their polar interactions with carbon dioxide being stronger than any interactions with nitrogen. With the high solvent resistance of the PEIs, they also will not dissolve when in contact with most solvents. The problem with PEIs over polyamides is their permeability. The inert gases that are free to go back into the atmosphere have trouble getting through the PEI, making them difficult to use in filtration, but this study was meant to find ways to fix that. **Figure 12** shows the structures of the polyamide and the PEI that were studied.<sup>12</sup>



**Copoly(ether-amide) PEBAX® MH 1657**



**Aromatic-aliphatic copoly(ether-imide)**

**Figure 12:** Generic structures of the polyamide and the PEI used by Tena et al.<sup>12</sup>

In figures and tables shown for this study, PEBAX is in reference to the polyamides used, just with their commercial name, and PEO is in reference to the PEI with the number of repeating units following, with two thousand, six thousand, and ten thousand repeating units. Much of the permeability was shown to work best slightly under the  $T_m$ , or the melting point, because of the amorphous nature of the polymer at this temperature. The percentage of PEO in the polymer,  $T_g$ ,  $T_m$ , and percent crystallinity of each tested polymer is shown in **Table 4**.<sup>12</sup>

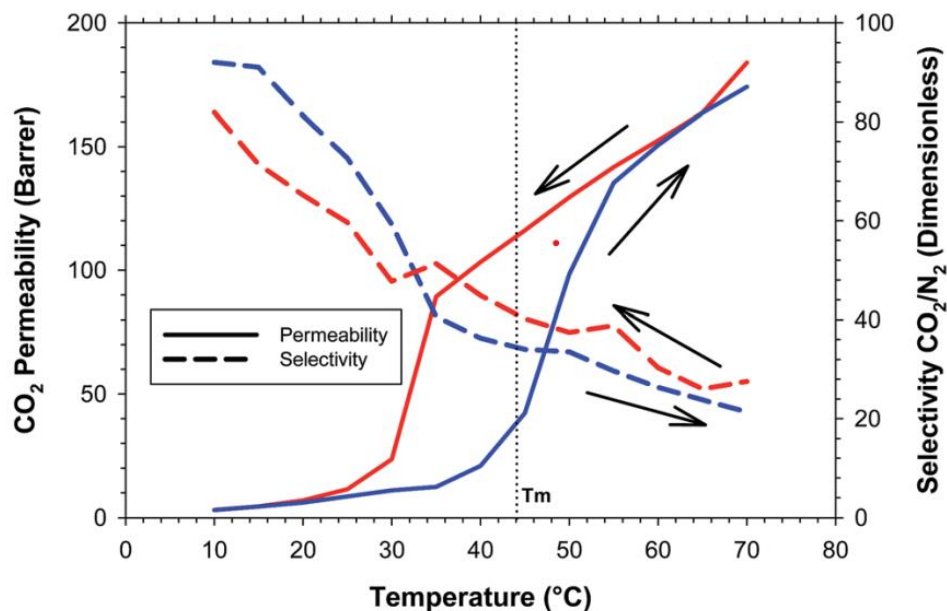


**Table 4:** Summary of the characteristics of each polymer used in the experiment.<sup>12</sup>

<b>Copolymer</b>	<b>% PEO theoretical</b>	<b>Polymer <math>T_m</math>/°C</b>	<b>Crystallinity/%</b>
PEBAX® ethanol/water	57	15.3	19.4
PEBAX® Nmp	57	14.4	14.3
PEO2000	53.9	29.7	0.25
PEO6000	57.0	32.9	27.2
PEO10000	57.6	44.6	36.8

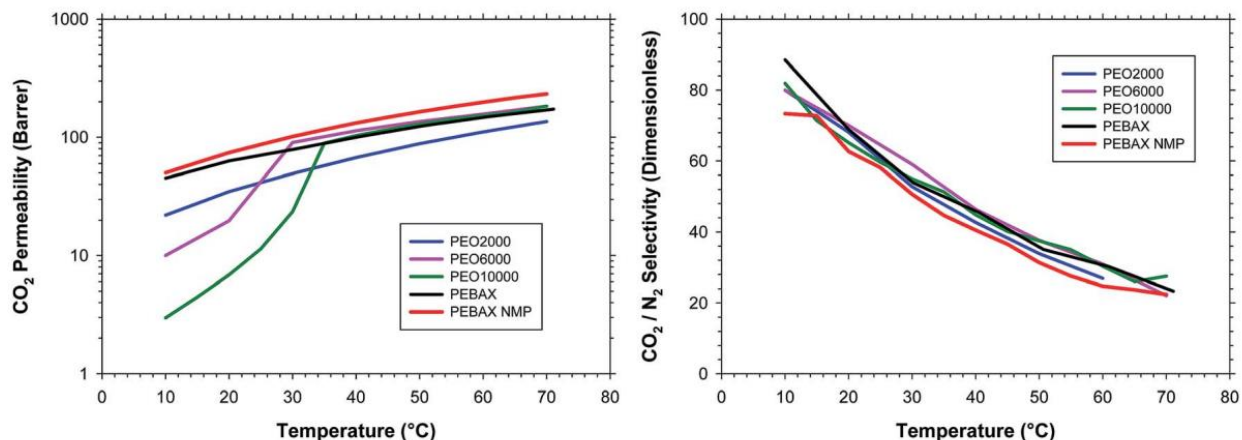
As shown in **Table 4**, both PEBAX samples contained approximately 57% PEO and a low  $T_m$  relative to the other samples. PEO10000 was the most interesting sample and the one the group moved on with having a 57.6% PEO content, the highest  $T_m$  of the group at 44.6°C and the highest crystallinity at 36.8%.<sup>12</sup>

Permeability and selectivity are inversely related to each other. The more permeable a substance is, the less selective it is. Since this is the case, there is a sweet spot to look for where you get the most permeability and the most selectivity. In the case of this study, gases like carbon dioxide and methane need to be captured while inert gases like nitrogen and oxygen need to go through the polymer. **Figure 13** shows the permeability of carbon dioxide and nitrogen through PEO10000 as a function of temperature in two trials.<sup>12</sup>



**Figure 13:** Permeability of carbon dioxide and selectivity of carbon dioxide and nitrogen through PEO 10000 as a function of temperature.<sup>12</sup>

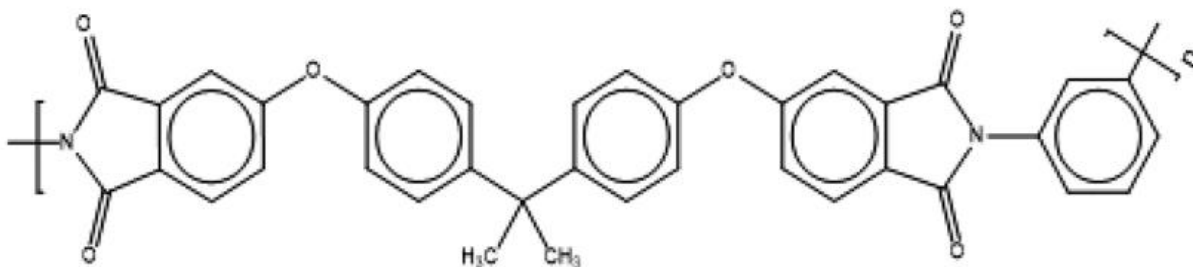
At each step of the testing process for permeability, the temperature the instrument increased to was allowed to stabilize and stay at equilibrium for a long period to ensure that any crystalline part of the solid that was going to melt, would melt, in contrast to a DSC measurement which shows its measurements as a function of heat flow. In **Figure 13**, the heating process is shown in red, and the reverse process is shown in blue. Both processes are also indicated by the direction of the arrows. Because of this process, there is a sharp increase in the permeability visible near the melting point. It was noted that similar effects were seen with PEO6000, but with a lower percentage of crystallinity, the change was not as drastic. The other three polymers had no significant changes due to temperature. Shown in **Figure 14** are separated permeability and selectivity graphs, where we can see the difference between the amide and imide polymers. Because of the PEIs crystalline nature, there is a spike at the  $T_m$  for permeability and the selectivity is comparable for each polymer.<sup>12</sup>



**Figure 14:** Separate permeability and selectivity for each polymer in the study by Tena et al. showing the effects of crystallinity in PEIs.<sup>12</sup>

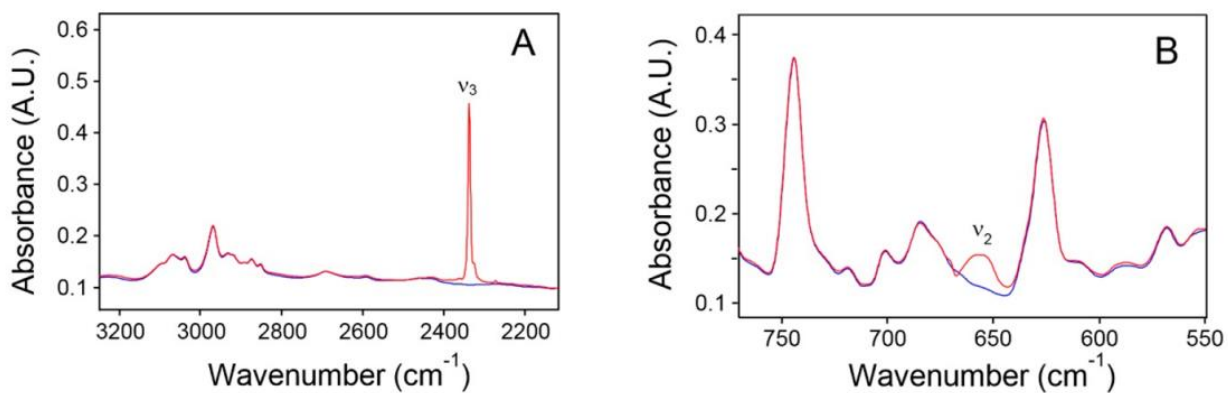
The largest note about **Figure 14** is the difference between PEO2000 and the other PEIs. It seems more comparable to the PEBAX samples in terms of permeability, while still being the same structure and backbone as the other PEIs. Another notable point is how PEIs showed a two-step decomposition at temperatures above 350°C, making it easy to see when they need to be replaced as they are less thermally stable while the PEBAX showed a one-step decomposition at 350°C. As said in the study, “the properties can be tuned to some extent by simply varying the aromatic composition of the copolymer,” which emphasizes the versatility of these specific PEIs in a wide range of applications.

In a similar study conducted by Scherillo *et al.*, interactions between PEIs and carbon dioxide on a molecular level were studied. Carbon dioxide was frequently shown to have weak interactions with the PEIs, but the work done in the study showed this using infrared (IR) spectra as well as many thermodynamic techniques. The group used an unsubstituted 4,4'- PEI, as shown in **Figure 15**.<sup>13</sup>



**Figure 15:** Molecular structure of the PEI used in the study by Scherillo et al.<sup>13</sup>

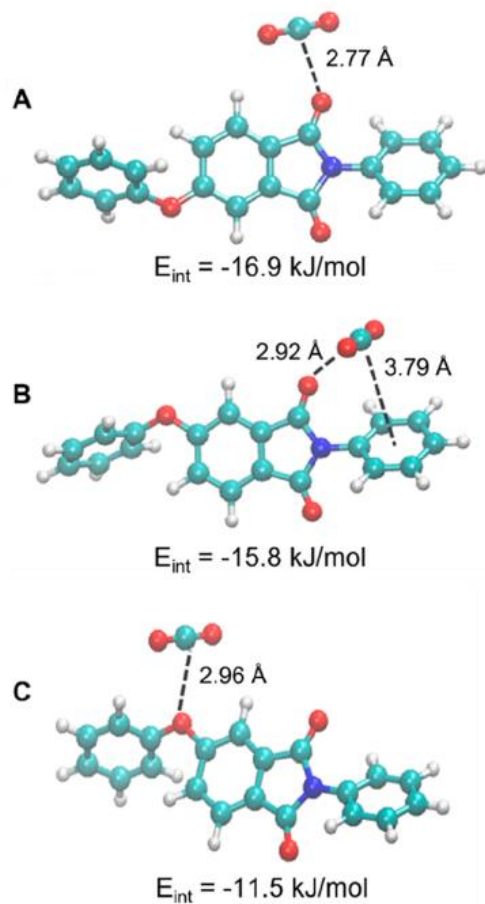
The samples were exposed to a layer of gaseous carbon dioxide during testing to see the interactions between the gas and the polymer film. The two modes,  $\nu_3$  and  $\nu_2$ , represent the antisymmetric stretching of carbon dioxide and a bending mode that is weaker and slightly overlapped by bands in a section of fully dried film from the polymer respectively. Both sections also showed a red shift in the presence of carbon dioxide, which is a shift in the wavelength to a longer wavelength, showing a decrease in energy.<sup>13</sup>



**Figure 16:** FTIR spectra showing  $\nu_3$  and  $\nu_2$  with the blue section being the fully dried polymer film.<sup>13</sup>

Scherillo *et al.* noted that there were three different places on the polymer backbone where the carbon dioxide could bind.<sup>13</sup> In reference to **Figure 15**, the carbon dioxide seemed most interested in interacting with the oxygen of the imide group, a combination of the oxygen on the imide group and an ending phenyl group on the right, and the carbonyl oxygen of the

ether. As will be explained further, the interaction between carbon dioxide and carbonyl will be the most interesting. This is shown in **Figure 17**, with the hydrogen atoms in white, the carbon atoms in gray, oxygens in red, and nitrogen atoms in blue, as well as the interaction distances and energies.<sup>13</sup>



**Figure 17:** Locations of most interactions between carbon dioxide and the PEI.<sup>13</sup>

**Figure 17** shows that the interaction energy of carbon dioxide with the carbonyl group is the preferential site, since the energy is lowest there. It is believed that this is the case due to the proximity of the two other phenyl rings near the carbonyl, making the interaction more stable. Being able to predict the interactions between the polymer and carbon dioxide is important for chemical engineers so they can build efficient and effective filters by knowing the permeability,

melting point, and selectivity of the polymer. The point of this study was to determine if PEIs would be good for gas separation in a laboratory setting, but it can also be used in conjunction with the previous study by Tena *et al.* to filter out harmful gases on a larger scale as well.<sup>12</sup> From this study, it can be concluded that there is a chance PEIs could be used as a sort of net to capture carbon dioxide, and help take a step towards more sustainable and less harmful industrial waste.

Overall, PEIs are a diverse and easily manipulated class of step-growth polymers that have a wide variety of applications. What the consumer receives is multipurpose, though this is reflected in the price. Through a variety of monomers, many different characteristics can be achieved, with some common goals being chain stiffness, melt processibility, and chain interactions. Solubility is limited because of PEI's inherent chemical resistance, which can be good commercially, but more difficult when it comes to running tests. Some of the downfalls of PEIs can be adjusted on the molecular scale to meet the standards set forth by the customers, hypotheses by scientists, or by necessity, while giving up some other properties in exchange. Many studies have been done on the possibilities that PEIs provide and many more will be done to potentially give them more qualities, improve upon the existing qualities, and potentially make it more affordable. PEIs are used in so many unseen applications the public uses every day to keep them safe, from automobile parts, sterilized pans, flame retardant aircraft, air filters for industrial gas separation, and many others. The uses are endless, and they bring many good qualities that have already improved the quality of life of much of the world.

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