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Application of Disordered Organic Semiconductor Theory to Low Temperature Curing of Epoxy Resins

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Abstract: The steep autocatalytic feature in a highly accurate DSC study of the heat rate from curing an epoxy resin with piperidine at 27.5 Deg C could not be explained using chemical kinetic power laws usually applied to curing epoxy resin products at higher temperatures. The theory of disordered conjugated organic semiconductors developed in the last decade has been applied to the observed heat rate data. Four heat rate sources have been identified to completely account for the experimental data. Two of the four sources generating 80% of the heat are consistent with mobility change of ion pairs indicating that the low temperature cure follows an organic semiconductor mechanism. It was shown that autocatalysis did not begin until about one fiftieth of the epoxy rings were opened (ignition). After ignition the heat rates of two propagation mechanisms grow exponentially. One charge transport mechanism generates a small heat rate but grows immediately after ignition due to an increase in ion pairs by the dopant (piperidine). The second mechanism appears later but becomes dominant, peaking at 50% completion, where the heat rate is about 50 times higher than the start of the first mechanism. The rate increase is attributed to localized energy sites that lower the LUMO level closer to the HOMO level of the monomer increasing the mobility (heat rate).

Keywords: Epoxy resins, kinetics (polym), calorimetry, diffusion, organic semiconductors.

1. INTRODUCTION

In 1954, a series of experiments was run as part of a thesis to study the rate of polymerization of the epoxy resin. In 2006, the results were analyzed and published [1], hereafter referred to as I. Some of the delay was due to the steep autocatalytic behavior of the heat rate that didn't fit the expected chemical kinetic power laws. By using spreadsheet tools and improved computational methods, specific features of the autocatalytic reaction emerged. In I, it was shown that the secondary amine, piperidine, reacted with the epoxy monomer at the outset following a bimolecular reaction rate. Since the ratio of amine to epoxy was well below unity, it would follow that the amine would be depleted and the heat rate would shift from forming C-N-C bonds (aminification) to C-O-C bonds (etherification) when the epoxy ring is opened. Before the amine was depleted, however, the heat rate accelerated by about a factor of ten before falling to a zero heat rate. As the heat rate declined to zero it was shown to follow a bulk diffusion rate law. The bimolecular and the bulk diffusion mechanisms have been recognized in the vast literature on curing of epoxys. In I, models were developed to calculate these two heat rates over the course of the experiment. But, they only contributed about 20% of the observed total heat. This paper extends further the analysis of the other 80% described in I. The raw data provided in I has been used here also.

An autocatalytic heat rate for epoxys so far has been attributed to the following concepts:

1. Two bimolecular reaction rates, one catalyzed by OH that grows from an initial uncatalyzed reaction [2, 3].
2. A reaction producing a ternary amine that can catalyze a reaction with an OH group to initiate an additional propagation step [4].

The cited references carried out heat rate experiments at temperatures higher than I. An activation energy determined by the authors was used to adjust the rates to 27.5 deg C. On comparing the chemical reaction models of Riccardi & Williams (RW) [2] and Horie [3] with the experimental data in I, the following distinctions appear:

	Ref 2,3 Models	**Ref I Data**
Rate vs Degree of Completion	Convex Shape	Concave Shape
%Completion @ Max Rate	<30	~50
Rate @ t(max)/Rate @ t=0	<3	~10

The RW and Horie models have been very useful in explaining the kinetic behavior at normal curing temperatures but they do not have the flexibility to fit observations at room temperature. The extrapolated results using the ternary amine rate data [4] show that there is little variation in the combined rate over the first 100 hours. Tanaka and Kakiuchi [5] studied the reaction of phenyl glycidyl ether, a monoepoxide, with various ternary amines and found that the products

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were less crystalline and had lower molecular weights when cured at temperatures above 50 deg C. These distinctions lead one to examine more thoroughly the basis for a new mechanism different from the conventional chemical kinetic formulas applied at higher curing temperatures. In I, a negative ion transport mechanism was suggested. In this paper the evidence will be developed further, but the author now feels that a more general expression, such as ion pair, is more appropriate until specific mobility measurements are made. The opening of an epoxy ring by an amine allows a hydrogen ion to be shared between the C-O fragment and the C-N fragment. The result is an ion pair that may have a partial +/- separation as mobile charged species.

2. ION PAIR GROWTH AS A HEAT SOURCE

Figure **1** is a copy of the results of one of the three heat rate experiments in I. Three distinctive heat rate mechanisms were found due to: (a.) direct bimolecular reaction between the amine and the epoxy, (b.) bulk diffusion, (c.) Gaussian fit to the heat rate data not accounted for in (a) or (b). The residual heat rates in (c) were normalized around the max residual heat rate. The sigma value for the Gaussian fit was adjusted to a value that produced the smallest deviation from the overall experimental data. When these three heat rates were summed, the result was below the experimental heat rate data only at the lower shoulders of the Gaussian curve (compare red vs yellow dots). Similar deviations at the lower shoulders were observed for the other two experiments reported in I, an indication that there may be a separate fourth heat source in the heat rate profile.

In this paper, the calculated heat rate contributions from the direct amine reaction and bulk diffusion were subtracted from the experimentally observed heat rate data at each time of measurement. The residual experimental heat rate data were then normalized to the maximum residual heat rate for each of the three experiments. Figures **2a**, **b**, **c** show the normalized heat rate as a function of time for the three experiments where the amine to epoxy ratio was respectively 0.034, 0.100 and 0.170. The residual normalized experimental curve (red) is shown without data points to articulate the differences. Also included in Figures **2a**, **b**, **c** are two curves (n trial and sigma models) for expressing the calculated Gaussian heat rate that was described in I. Both curves (lightly shaded yellow and green) are essentially coincidental. The Gaussian and the adjusted experimental curves differ only at the lower shoulder. This difference may be regarded as a fourth heat source operating simultaneously with the Gaussian heat rate model, except that this fourth heat source starts before and lasts beyond the Gaussian period of dominance at a much smaller heat rate. The focus of the analysis will be on the small heat rate difference on the upside of the experimental heat rate curve. However the features on the downward slope have a qualitative equivalence to what will be described below. Detection and measurement of these small differences was possible because of the 4 decimal accuracy of the DSC used in I. Most modern DSCs do not have this level of accuracy.

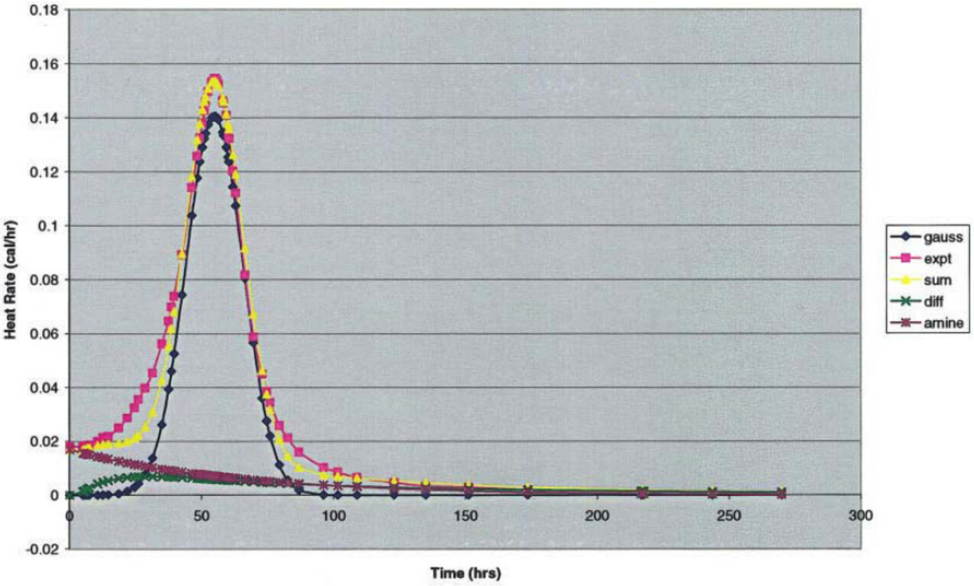


Figure 1: Comparison of rates for Expt 170. [Color figure can be viewed in the online version, which is available at www.interscience.wiley.com.] Taken from Ref [1] Figure 16.

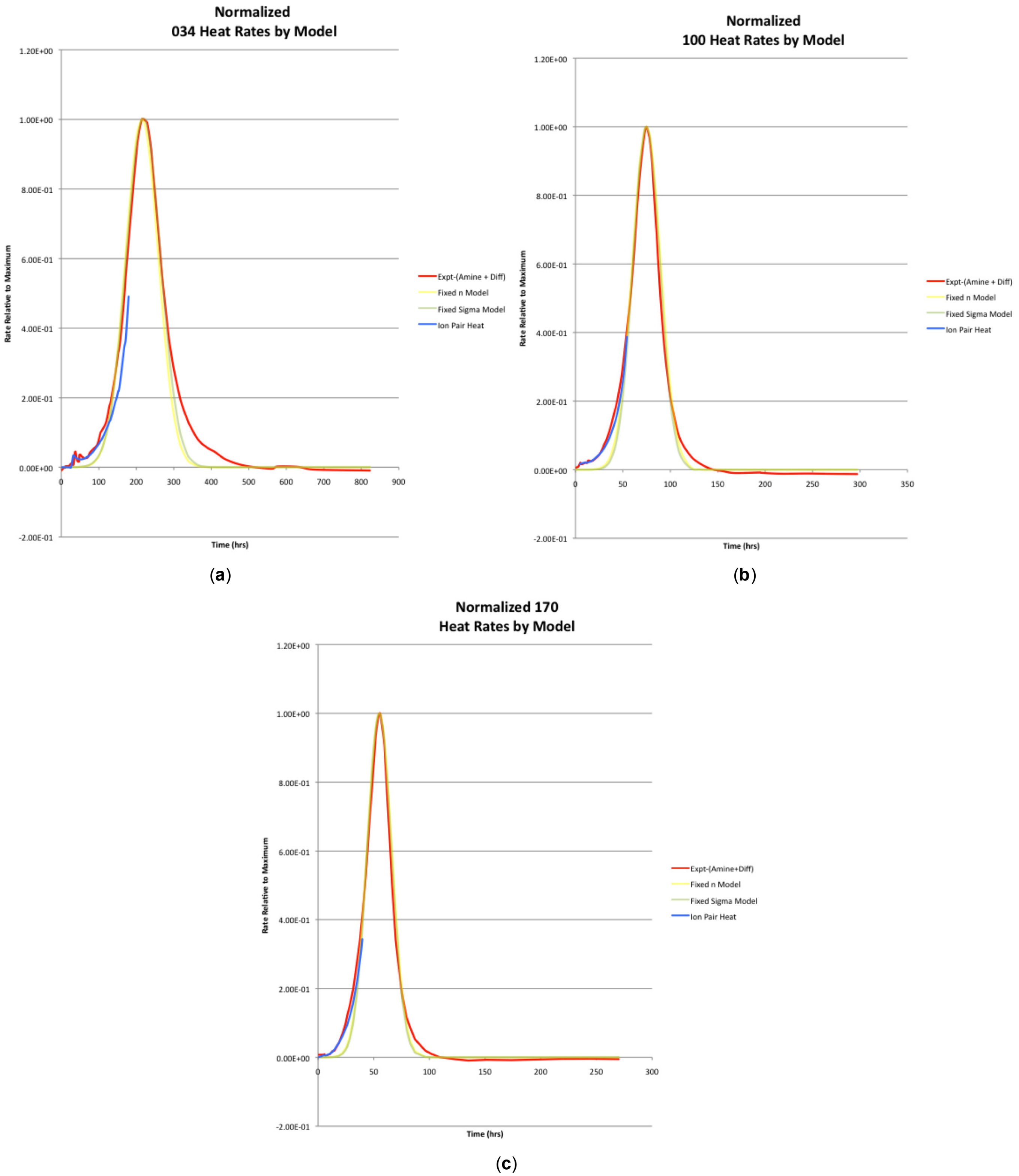


Figure 2: (**a**) Normalized 034 Heat Rates by Model. (**b**) Normalized 100 Heat Rates by Model. (**c**) Normalized 170 Heat Rates by Model.

The initial heat rate was apparent from the outset and was steady for a brief period before an increase in the heat rate was detected. The time when an increase in the heat rate occurred was different for each amine content. For .034, it was about 30-40 hours, for .100, 3-4 hours and for .170, 0 hours. The analysis in I showed that these ignition points for an accelerating reaction occurred when the three experiments had generated about one ion pair per 50 epoxy rings. The ion pairs were the result of:

1. An equilibrium mass action between the OH in the body of the monomer and the available piperidine.
2. A direct amine reaction with the monomer to open the epoxy ring.

The first statement is not heat producing but the second is. After ignition the heat rate was shown to follow a linear relation between the reciprocal of the heat rate and the time for a significant part of the early stages (See Figs. 6,7,8 in I). This type of reaction rate equation is empirical and has no precedence in mechanistic studies but it was useful for defining the ignition conditions described above. Figure **2a**, **b**, **c** also shows the contribution to the heat rate from this dubious reciprocal rate/time relationship. This portion is labeled Ion Pair Growth (IPG) heat rate for reasons that will be justified later. One can see that this heat rate increment (blue curve) accounts for the incremental difference between the sum of the heat rate models and the experimental heat rates in I. When it is added as a heat rate source, it coincides with the residual experimental data for all three amine contents. Compare blue and red curves. It appears that the heat rate before ignition follows the expected chemical kinetic laws but at ignition a new mechanism emerges. After ignition only ion pair production continues to increase linearly as not all of the amine has been depleted, but there is an apparent exponential rise in the IPG heat rate in Figure **2**. It appears now that the linear reciprocal heat rate relationship with time, found empirically in I, is simply an approximation of an exponential term expanded in an infinite series over a narrow time period after the other heat sources are subtracted out. The empirical linear reciprocal relation derived in I may include the early stages of the Gaussian heat rate. Therefore the period of IPG heat rate may be shorter than the range of the blue curves shown in Figure **2**.

It is well known that epoxy resins have limited electrical conductivity during the cure period. It is initiated by amine additions and changes exponentially. Therefore it is reasonable to consider that the mobility of a charged species might be a measure of the heat rate of reaction. The IPG and Gaussian heat sources have exponential behavior with time. Mobility can also change exponentially according to the emerging theories for disordered organic semiconductors [6]. In the next section, adaptation of this theory to the results shown above will be examined.

3. CONCEPTUAL FRAMEWORK FOR DISORDER-BASED MODELS

The extensive review of charge transport in organic semiconductors by Baessler and Koehler [7] was used to set up framework for applying the theory. Mobility of a charged species is generally the product of three factors [6].

1. The number of charged species.
2. Increased disorder changing the distribution of energy states in the band gap.
3. Decreasing distance between mobile ion and a trap to increase the overlap of wave functions.

The last two are often exponential. If it is assumed that the ion pair concentration is a measure of the mobile species then the net change in mobility (M) from the start of ignition (i) through the ion pair growth period (t) is shown in Eqn 1. After ignition ion pairs are produced only by the remaining piperidine. Heat rates from bulk diffusion, IPG and Gaussian modes are propagation steps that only sustain ion pair concentration.

$$\Delta M = K * (C(t)/C(i)) * [Exp(-(\Delta E/2\sigma)^2)] * \{Exp(d(i)/d(t))- Exp\ (1)\} \qquad \text{Eqn (1)}$$

where,

$C(t)$ is the ion pair concentration

$d(t)$ is the mean distance between overlapping wave functions

ΔE is the energy change at a local site due to a dopant (ion pair).

σ is a term measuring the spread of energy states in a Gaussian format

K is a constant to convert to the proper units

$d(t)$ is assumed to be equivalent to the inverse cube of $C(t)$ for amorphous systems. Therefore the first and third factor in Eqn (1) may be expressed in terms of ion pair concentration with a linear and exponential component. During the IPG period only the concentration changes with time. The second factor (corresponding to Item 2 above) that involves ΔE and σ

does not change since the reaction is the same at each new ion pair site.

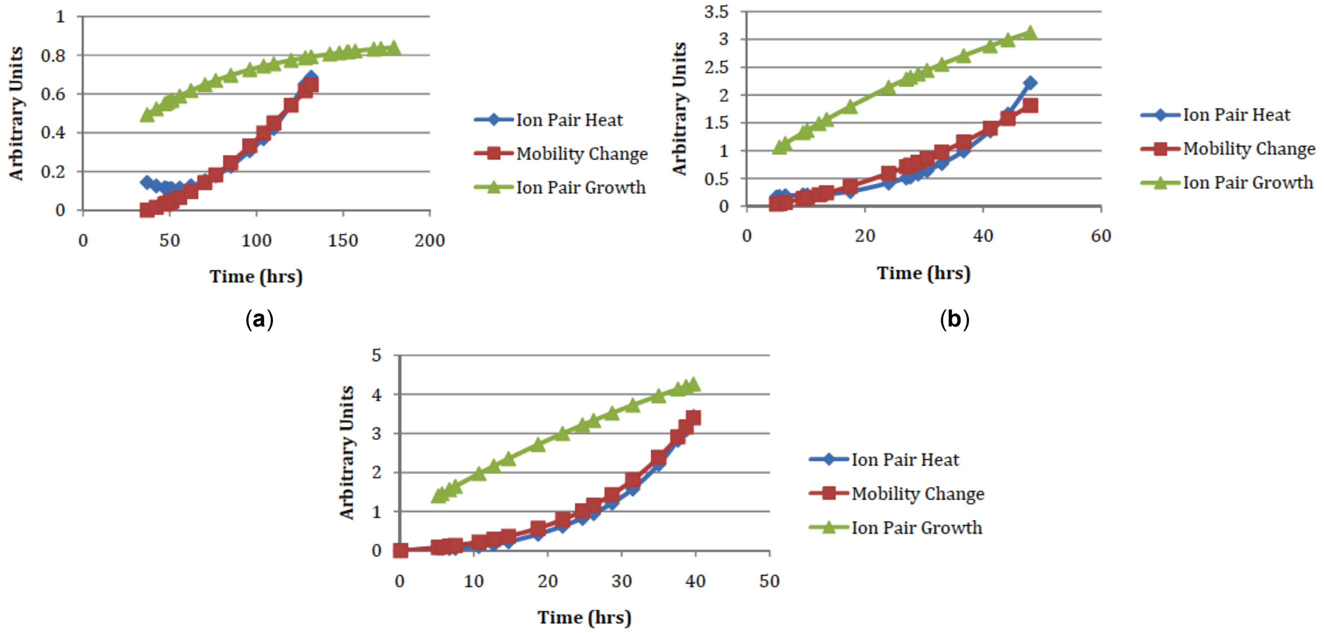
Figures **3a**, **b**, **c** show that the calculated IP growth, C(t), is nearly linear with time. The value is leveling off more in the 034 data because the available piperidine is nearing exhaustion. If it is assumed that the change in mobility is proportional to the change in the measured change in IPG heat rate then they should have the same profile over the IPG period. The profiles are shown also in Figure **3** for all three experiments after adjusting with scaling factors to show the results on one graph. The starting time is at ignition when the oligomer becomes semiconducting. Some irregularities are apparent here due to the difficulty to resolve very small heat rates operating simultaneously. The extent of the 034 IPG period was trimmed back in time as the Gaussian heat rate is beginning to dominate. The ion pair heat rate was defined by the empirical reciprocal relationship that could extend into the Gaussian period and was adjusted accordingly. It appears therefore that the observed change in IPG heat rate corresponds to the change in mobility in the disordered conjugated epoxy system in agreement with theoretical concepts [7].

Application of Equation 1 to the Gaussian period may indicate a different outcome since the ion pair concentration becomes relatively level due to near exhaustion of the amine. Yet the data show a very large increase in the heat rate. If mobility is a measure of this increase then the Gaussian heat rates may result from a change in ΔE. The density of energy states in the band gap will be analyzed in section 5.0.

4. PROPAGATION STEPS IN THE EPOXY CURING PROCESS WITH PIPERIDINE

After piperidine reacts to form a ternary amine, the epoxy ring is opened creating an ion pair. The ternary amine has no further capacity to create another ion pair unless a hydroxyl group is added to react and convert it to a quaternary form [4]. If there is no added OH group then an open epoxy fragment links to the SN2 position on another epoxy ring regenerating a new fragment and creating a C-O-C bond (etherification). Bulk diffusion, Ion Pair growth and Gaussian mechanisms all propagate in this way. They continue to operate until the epoxy rings are exhausted or until the mobility of the ion pair is arrested. In I, it was shown that bulk diffusion mechanism was the last propagation step to generate heat. Its shutdown is often attributed to the entanglement of clusters restricting random movement of reacting species. Whereas the IPG and Gaussian propagating steps were observed to end earlier and showed an exponential rise and fall,

The IPG propagation step starts immediately after ignition and the Gaussian propagation starts later when the fraction of ether bonds is larger. Initially at ignition when there are very few ether bonds, the IPG heat rate



(**a**) (**b**)

(**c**)

Figure 3: (**a**) 034 Ion Pair Growth vs Ion Pair Heat. (**b**) 100 Ion Pair Growth vs Ion Pair Heat. (**c**) 170 Ion Pair Growth vs Ion Pair Heat.

is about 1/50 (0.02 vs 1.0 in Figure **2**) of what is observed at the maximum. The IPG rate continues to increase by a factor of 5 due to ion pair growth described in Section 3.0 above. The Gaussian rate mechanism adds another factor of 10 to reach the maximum heat rate at about 50% completion. While both mechanisms peak at 50% and decrease thereafter due to a depletion of epoxy rings, the Gaussian peak appears to dominate only when both ether bonds and epoxy rings are significant

In I, it was shown how an equivalent statistical treatment could describe the residual experimental data by using the number of trials, n, to measure the spread of the Gaussian heat rate around a maximum instead of a variance value. The experimental data had the best fit to this model when the number of trials was about 25 (+ or – 1) for all three experiments. At ignition when the oligomer becomes semiconducting, about 50 epoxy rings are associated with each ion pair. At 50% completion when the heat rate is at maximum and the ether bond and epoxy ring populations are equal, there are 25 ether/epoxy pairs available for each ion pair, an indication that there is an associated arrangement between them that increases the mobility of an ion pair. At 25 trials the Gaussian distribution is essentially the same as a binomial distribution of 25 objects consisting of an ether bond/epoxy ring pair and an unpaired set. During the Gaussian heat rate period one can conclude that the mobility (heat rate) is proportional to the number of combinations of paired sets.

According to conjugated transport theory such pairing may be a geometric arrangement of strings of coordinated pairs or an activated complex with secondary bonding. It is expected that these arrangements are of short duration constantly forming and dissipating until a mobile ion pair species arrives to facilitate a reaction. At this point the analysis will take the view that the IPG and Gaussian propagating reactions are occurring by hopping of mobile ion species among a cluster of about 50 epoxy rings. Their mobility will differ due to an energy change in the distribution of states in the band gap.

5. FORMULATION OF DISORDERED STATES DURING THE CURE

The epoxy monomer consists of high potential energy centers around two epoxy rings and a spine or backbone that joins the rings. The backbone is basically inert to energy changes at the ring but has a conjugation link for supporting a conduction band that can extend over the monomer and to n mers on a nanometer scale.

The Fermi energy for the unadulterated monomer can be set at 0 ev at the top of the valence band. Since the monomer exhibits no conductivity, the valence band is full and the conduction band is empty. If the backbone of the monomer is unchanged, the Fermi level can be expressed in terms of the Gibbs free energy of formation of the epoxy group using the values for ethylene oxide. The conduction band will be the first excitation energy of oxygen containing a pair of unbonded electrons. The first excitation level is about 0.9 ev. [8]

As the monomer is adulterated with a small amount of amine, an ion pair forms and electrical conductivity begins. Some of the epoxy rings open and create C-N-C and a few C-O-C bonds that bring disorder in the energy states above and below the Fermi level. As the reaction proceeds to the critical concentration (ignition) the disorder increases enabling a broadening of the density of states (DOS) to support an increase in conductivity allowing the most mobile species to move across the monomer boundary and cover nanometer distances. At this point the backbone of the monomer can act as a conjugated link to aid boundary crossover. The epoxy system becomes a disordered organic semiconductor. The heat rate is controlled by the mobility of ion species in new energy states filling the gap between the valence band and the conduction band. The new states are delocalized and can cause large changes in the mobility in the oligomer [7]. As etherification develops, localized sites change from the host (epoxy) to a guest (ether). If the free energy change of the epoxy to ether is negative, then energies of both guest excited state (LUMO) and the guest normal state (HOMO) are lowered by the same amount. When the LUMO (guest excited state) gets close to the HOMO (host normal state) then the mobility is slowed less by the local disturbance [7].

To develop a chemical basis for estimating the mobility change (i.e. heat rate change), the Gibbs free energies were estimated from data in the NIST files [8] for several model compounds related to the curing of epoxys. They are ethylene oxide (host), dimethyl ether (guest1) and dioxane (guest2). Each represents a different chemical form of a C-O-C fragment. The backbones attached to these compounds are considered unchanged energy wise. The guest 1 dopant represents the local energy changes at ignition in the IPG period. The guest 2 dopant represents the local energy changes during the Gaussian period. The maximum heat rate occurs at 50% completion. Ether/Epoxy fragment pairs peak at this point. The geometric framework of a dioxane molecule is a reasonable basis for a dioxane-like activated complex to exist to enhance the mobility. Dioxane is a dimer of the C-O-C fragment and its free energy of reaction must be divided by a factor of 2 for energy change comparisons. The calculated Gibbs free energy data below show that guest1 formation lowers the localized site -0.66ev but guest2 lowers the localized level even further to -0.85 (-.66-.37/2).

Ethylene oxide + 1 Hydrogen = Dimethyl ether (Guest 1) -63.8 kj/mol (-.66 ev)

2 Dimethyl Ether + 2Hydrogen = Dioxane (Guest 2) -35.8 kj/mol (-.37 ev)

The energy levels for the localized reactions are summarized in Table **1**.

The LUMO level is 0.9 ev above the HOMO level of all the local site products. But, the "Dioxane complex" is closer to the host HOMO level than the ether LUMO level which differentiates the IPG and Gaussian propagation steps discussed in the previous section.

The second factor in Eqn 1 shows the distribution of localized energy states (DOS) term proposed by Arkhipov and others [6] for conjugated organic semiconductors. The first and third factors in Eqn1 were linked previously to the mobility change during the IPG period. During the Gaussian propagation period, there is little change in ion pair concentration as most of the amine has been consumed and the effect is small compared to the Gaussian heat rate.

The DOS impact is an expression that compares the difference between the HOMO level of the host material (epoxy ring) and the LUMO level of the guest material as a measure of the impact on mobility. The spread in energy states about the LUMO level is characterized by the term σ in energy units defined in Eqn 1. The value is subject to much discussion in the theory as it may be influenced by vibrational and geometric modes associated with the overall oligomer system. Since the Gaussian heat rate curves shown in Figures **2a**, **b**, **c** are Gaussian, σ was determined from the normalized experimental data by comparing the discrete values at several time values to match a uniform rise over the Gaussian peak relative to the values at maximum at the peak. This exercise showed that the best fit for σ is 0.085 ev.

By incorporation of the ΔE values in the third column of Table **1** to represent the energy difference and the σ value to represent the spread, the DOS impact is listed in the fourth column of the table for three types of localized reaction products. Ethylene oxide represents the pure state and the DOS Impact on mobility (heat rate) is negligible. The localized ether fragment has a LUMO level 0.24 ev above the HOMO host level and its impact raises the mobility from negligible to about 0.017 of the maximum rate. The localized "dioxane" fragment has a LUMO level .05 ev above HOMO host level and the DOS Impact is 0.82 of the maximum heat rate. The ratio of the mobility (heat rate) between ether fragment and "dioxane" fragment is about 0.017/0.82, corresponding to the observed heat rate ratio of .02/1 at ignition and at the maximum heat rate.

These calculations using disordered energy state models are consistent with the heat rate observations however their validity will require experimental confirmation of ion mobility during cure. The inference that an activation complex akin to a dioxane structure requires further study. The epoxy ring and the ether fragment (C-O-C) both have planar triangular shapes with angles at the oxygen vertex of about 120 deg. These fragments are polar and one would not expect them to align themselves in planar array as partners. The dioxane structure is not planar but has two forms: chair like and boat like shapes. These two shapes can be conceived as epoxy and ether fragments linked forming the chair seat or boat bottom. Because the linkage is between two positive poles there is no attraction to form a complex. However if a negative ion

Table 1: Calculated HOMO and LUMO Energy Levels and their DOS Impact for 3 Local Products: Ethylene Oxide (host), Dimethyl Ether (guest 1) and Dioxane (guest 2)

Local Product	HOMO ev	LUMO ev	DOS Impact
Ethylene Oxide	0	+0.9	< .00001
Dimethyl Ether	-0.66	+0.24	0.017
Dioxane	-0.66-0.37/2=-0.85	+0.05	0.82

such as an open epoxy fragment is inserted in the chair seat or boat bottom the repulsive polar interaction could be offset by the negative charge nearby creating a dioxane like complex with stability sufficient to promote the reaction (etherification)[9]. The negative ion fragment eventually bonds to the epoxy fragment at the SN2 site, opens the ring, creating a new negative ion fragment. The original ether fragment breaks off and the mobile ion moves in the energy band to reform the dioxane complex elsewhere. The concept is supported by the fact that "dioxane" lowers the LUMO level to promote greater ion mobility. The symmetry of the dioxane arrangement may add to the stability of the complex. During early stages of the cure not many epoxy/ether pairs are available. The LUMO level for ether is not as close as the dioxane LUMO level is to the HOMO level of the epoxy monomer. The reaction rates are smaller but grow during the IPG period until it is surpassed by the Gaussian propagation by an order of magnitude or so.

5. OTHER RELATED ISSUES

One of the drawbacks of curing the epoxy resin at low temperatures is the lack of complete reaction. The heat of reaction for complete aminification is consistently about 100 kj/equiv. The heats of reaction from the three experiments in I were: 56.4, 50.7 and 51.4 kj/equiv. The literature is not clear about the heat of reaction for etherification but it is expected to be around 100 since the principal energy release is the opening of the epoxy ring. Therefore the reaction in I was only half complete at room temperature even though the heat rate went to zero. From a semiconductor viewpoint, it means the range of ion pairs may be limited.

The epoxy system becomes a conjugated semiconductor when 1 out of 50 epoxys are disordered. If one assumes cubic symmetry, the ion pair in the center would influence fifty epoxy rings defined by a cube edge of about 3.1 nanometers. If one assumes an amorphous media, an ion pair component could migrate (hop) radially from its partner, its range would be an inscribed sphere of radius 1.54 nanometers within the cube. The volume of the inscribed sphere is about 15 cubic nanometers. The volume of the cube defining the onset of propagation is 30 cubic nanometers. If the propagation sweeps radially from the ion pair anchor at the center, the corners of the cube may not be affected and no reaction there occurs by hopping. Thus only half of the epoxy rings are available to be opened. The literature reports three different observations that support this range of mobility.

Studies [5] of curing phenyl glycidyl ether with ternary amines at room temperature showed that two fractions of the oligomer with >5 opened epoxy links accounted for almost half of the reaction. One fraction containing an average of about 8 linked openings showed 47-50% crystallinity that disappeared above 50 °C and/or with increasing amine additions. The crystallinity may be a result of partial ordering characteristic of a conjugated system.

Morgan [10] using the Eyring viscous flow model to determine activation volumes of amine cured DGBDA epoxys found that these systems are in the range of 9 to 12 cubic nanometers. This indicates there is a core cluster size in the oligomer.

By modifying a hydrogen atom wave function that has a Bohr radius of 0.053 nanometers to meet the conditions for a mobile ion moving with an effective mass of 0.135m in an epoxy dielectric medium of 4, one obtains a 1.54 nanometer radius. Therefore quantum relationships would be applicable up to this range of propagation.

6. SUMMARY AND CONCLUSIONS

The emerging theory of disordered conjugated organic semiconductors has been used to explain the heat rate changes during the curing of epoxy monomers with piperidine. The heat rate data for curing the diepoxide monomer at low temperatures and low amine/epoxy ratios were not compatible with chemical kinetic studies at higher temperatures and ratios of 1:1. The precise data from DSC type calorimeter used in the study identified specific breakouts of four heat rate sources, two of which were shown to fit the mobility changes predicted by the new theory.

Etherification has been somewhat of a mystery during conventional processing of epoxy polymers. This study shows that low temperature etherification is driven by electronic band theory when the amine content is a minor constituent. Creating such a band structure may depend on variations in the backbone of the monomer and the type of dopant used. The dopant creating disorder is the C-N-C bond formed by reaction with piperidine. The range of the mobile ion was shown to be around 15 cubic nanometers consistent with other experimental data. It may be possible to extend the range further as is being done with conjugated carbon compounds used for LED applications.

This study has not tried to determine which type of ion pair is controlling the reaction rate. Specific electrical conductivity measurements are needed at the nanometer scale to determine the most mobile ion: electron, holes, protons, bipolarons, etc. Many conjugated organic semiconductors have shallow traps to capture the mobile ion. The epoxy curing has deep traps that hold, react and regenerate a mobile ion. The chemical potential field around the traps replaces the external field often used to measure mobility in organic semiconductors.

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