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# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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| 1. AGENCY USE ONLY (Leave blank) | 2. REPORT DATE 1/11/93 | 3. REPORT TYPE AND DATES COVERED 1 March 1990 - 31 August 1993 |
|---|---|---|

**4. TITLE AND SUBTITLE**

Organic Materials that Respond to Molecules

**5. FUNDING NUMBERS**

DAAL03-90-G-0051

**6. AUTHOR(S)**

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**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

U.S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

ARO 27724.6-MS-SM

**11. SUPPLEMENTARY NOTES**

The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**

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**12b. DISTRIBUTION CODE**

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**13. ABSTRACT (Maximum 200 words)**

Materials have been developed in which symmetry and structure are tunable by control of the molecular size of one of the partners in the A.B pair. Materials have been studied in which a reversible crosslinking agent's concentration is used to control material properties. The two systems are understood in quantitative detail

94 2 08 100

94-04430

**14. SUBJECT TERMS** smart materials, hydrogen bonding, molecular recognition, reversible gelation.

**15. NUMBER OF PAGES**
12 (inclusive)

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED | 18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED | 19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED | 20. LIMITATION OF ABSTRACT UL |
|---|---|---|---|

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

# PROGRESS REPORT

## FIFTY COPIES REQUIRED

1. ARO PROPOSAL NUMBER:          27724-MS-SM

2. PERIOD COVERED BY REPORT:       1 March 1990 - 31 August 1993

3. TITLE OF PROPOSAL:             Organic Materials that Respond to Molecules

4. CONTRACT OR GRANT NUMBER:    DAAL-03-90-G-0051

5. NAME OF INSTITUTION:           University of Pittsburgh

6. AUTHORS OF REPORT:           A. D. Hamilton and S. G. Weber

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSHIP DURING THIS REPORTING PERIOD, INCLUDING JOURNAL REFERENCES:

    See attached sheet.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

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9. REPORT OF INVENTIONS (BY TITLE ONLY):

    None

## LIST OF MANUSCRIPTS SUBMITTED:

1. S. J. Geib, S. C. Hirst, C. Vicent, and A. D. Hamilton, "Molecular Recognition and the Design of Solid State Structures: Protonation Induced Conformational Change and Self Assembly of 2,6 Diamidopyridinium Phosphate:, J. Chem. Soc. Chem. Commun., 1283 (1991).

2. F. Garcia Tellado, S. J. Geib, S. Goswami and A. D. Hamilton, "Molecular Recognition in the Solid State: Controlled Assembly of Hydrogen Bonded Molecular Sheets", J. Am. Chem. Soc. 113, 9265 (1991).

3. S. C. Hirst, P. Tecilla, S. J. Geib, E. Fan and A. D. Hamilton "Molecular Recognition of Phosphate Esters: A Balance of Hydrogen Bonding and Proton Transfer Interactions", Isr. J. Chem. 32, 105 (1992).

4. S. J. Geib, C. Vincent, E. Fan, A. D. Hamilton, "Selbstorganisation zu einder Helix durch Wasserstoffbrückenbindung" Angew. Chemie, 105, 83 (1993). "A Self-Assembling Hydrogen Bonded Helix" Angew Chemie, Int. Ed., 32, 119 (1993).

5. S. J. Geib, E. Fan, F. Garcia-Tellado, C. Vicent, and A. D. Hamilton, "Supramolecular Self-Assembly based on Directed Hydrogen Bonding" Polymer Preprints, 34, 106-107 (1993).

6. A. D. Hamilton, E. Fan, S. Van Arman, S. J. Geib and J. Yang, "The Design of Artificial Receptors for Complexation and Controlled Aggregation" Proc. R. Soc. Lond. A., in press.

7. E. Fan, J. Yang, S. J. Geib, C. Vicent, F. Garcia-Tallado, P. Tecilla and A. D. Hamilton, "Supramolecular Self-Assembly based on Directed Hydrogen Bonding" Die Macromoleculare Chemie, in press.

8. Weber, S. G., Wise, E. T.; Hamilton, A. D.; Fan, E.; Vicent, C.; Tellado, F. G.; Geib, S. J., "Controlled Formation & Properties of Responsive Polymers", "Active Materials and Adaptive Structures", Knowles, G. J., Ed., 1992 pp. 32-39.

9. Wise, E. T.; Weber, S. G., "Quantitative Evaluation of a Smart Material: PVA-Borate Gelation and the Gel's Response to Diols" Polym. Prepr., 1993, 34, 215-21

Smart materials are materials that respond to their environment. In the presence of a *stimulus*, they recognize and discriminate, and react to produce some useful effect. The stimulus may be physical or chemical. The overwhelming majority of the work that has been done in this field has been in the area of physically responsive materials. The *response* may be physical, e.g. changes in conductivity, absorptivity, or viscosity may result, or it may be chemical, e.g. selective binding, adsorption, or decomposition may occur.

Chemically responsive materials are our interest. The basis for the chemical sensitivity is molecular recognition and competitive binding. Materials that respond in a physical or chemical way to molecules can be employed in a variety of applications that require chemical selectivity.

This report proceeds in two sections. The ultimate goal is to design smart materials. This requires two parts. One is the design of the molecular recognition chemistry, and the other is the design of the response that the material will give when it is exposed to the species to which it is sensitive (which we will call and agonist). The first part of this report covers the control of material structure through the process of molecular recognition. The second part covers the quantitative aspects of the physical properties of chemically responsive materials.

## 1. HYDROGEN BONDING CONTROL OF SUPRAMOLECULAR SELF-ASSEMBLY

### 1.1 SELF-ASSEMBLY IN THE SOLID STATE

The designing or engineering of solid-state structures is much more advanced than corresponding aggregation studies in solution[1]. Detailed investigations of crystal packing patterns from X-ray data have led to the delineation of various rules to predict the hydrogen-bonding arrangements in single- and two-component crystals.[2,3] However, there remains a strong need for hydrogen bonding motifs that form predictable arrays between subunits irrespective of the size and shape of the spacer groups. Such persistent H-bond networks would allow not only the more reliable prediction of solid state structures but also the construction of materials with a controlled positioning of potentially photo- or redox-active groups. Whitesides[4] and Lehn[5] have used the association of melamine and barbiturates to form hydrogen-bonded molecular tapes that maintain their basic structural features with different substituents on the two binding components. Our own work[6] has shown that the interaction between dicarboxylic acids and bis-acylaminopyridines is a strong and general one that survives in the solid state despite changes in subunit structure.

### 1.1.1 BASED ON HYDROGEN-BONDED RIBBONS

Protonation of diacylaminopyridine 1 with diarylphosphoric acid causes a 180° rotation around the C-N bond and formation of two intramolecular hydrogen bonds between the pyridinium-NH and CO groups. This directs the amide-NH groups outward to form two intermolecular H-bonds with bridging diarylphosphates. The resultant cocrystal takes up a ribbon structure with the pyridinium-phosphate hydrogen bond network at its core (Figure 1). This ordered arrangement leads to a segregation of anions and cations to opposite sides of the ribbon and recurs with other phosphate components including chiral binaphthyl phosphates.[6]
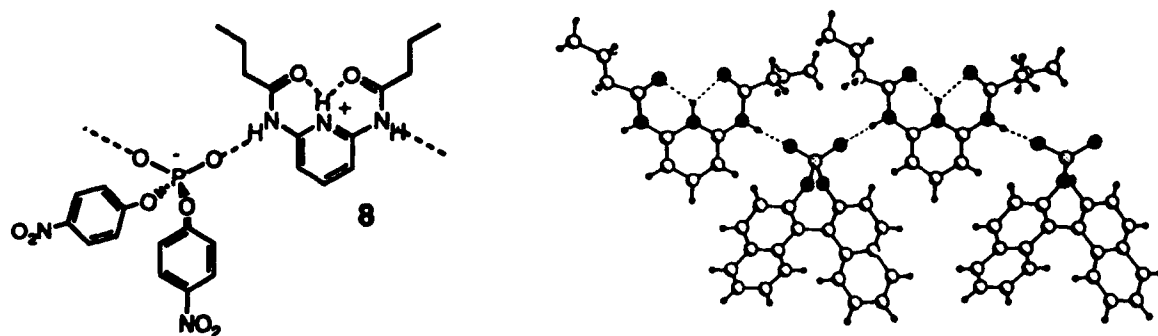
**Figure 1**

## 1.1.2 BASED ON HYDROGEN-BONDED SHEETS

The common translational H-bonded packing of diamides[3] can be induced to interpose a second component by incorporating strong bidentate interactions between the crystal partners. We have shown that the 2-acylaminopyridine/carboxylic acid pair provides a stronger interaction than the single hydrogen bond between simple diamides and can lead to polymeric aggregates as in Figure 2. This represents an elongated molecular sheet whose dimensions are imposed by the hydrogen-bonding network and the relative size match of the alternating components. Figure 3 shows the complex formed between biphenyldiamide 2 and
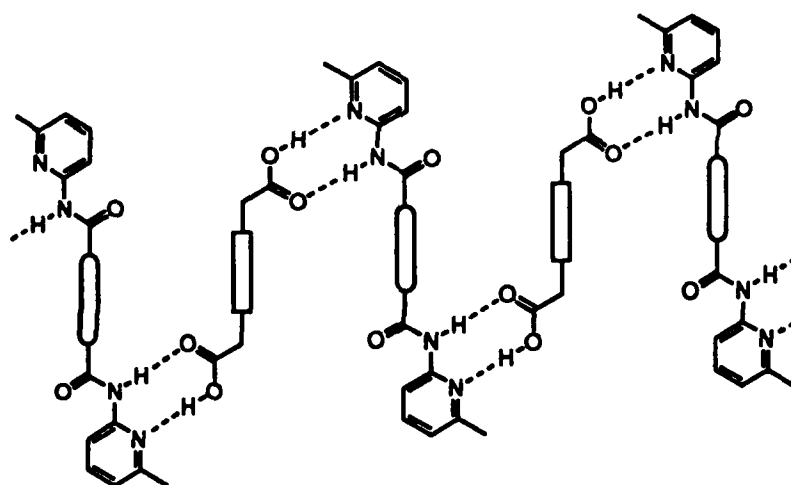


**Figure 2**

1,12-dodecanedicarboxylic acid. An almost flat sheet structure is taken up with a 73° slip or tilt angle between the polymethylene chains and the horizontal (defined by a line drawn through the pyridine-N atoms). This H-bonding motif is dominant and is retained despite changes in size of the molecular components. Indeed, the extent of the slip angle can be varied in a systematic and predictable way by changing the size matching of the diamide and diacid. Shortening the diamide spacer from biphenyl to naphthyl (≈2.2Å shorter) leads to a decrease in the slip angle to 60° (Figure 4). A subsequent shortening of the diacid to 1,8-

**2**
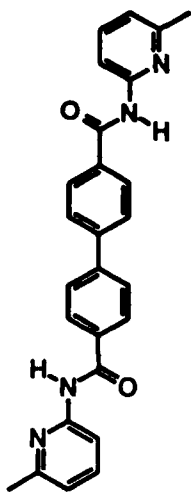


**Figure 3**

octanedicarboxylic acid increases the slip angle to the point where the two subunits are well-matched and the angle is ≈90° ( Figure 5). In this work we have identified a recurring hydrogen bond packing pattern that survives changes in the component structure. Such persistent motifs can form the basis of a wide range of functional and redox active polymeric aggregates.[7]
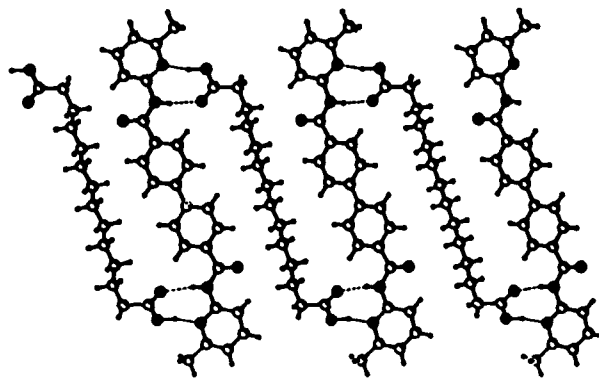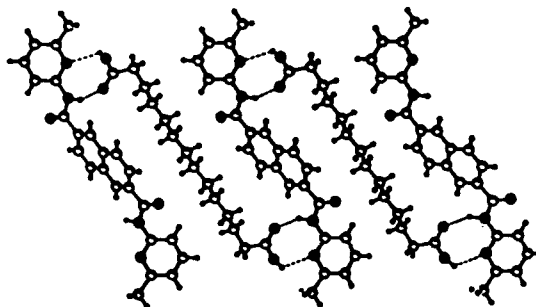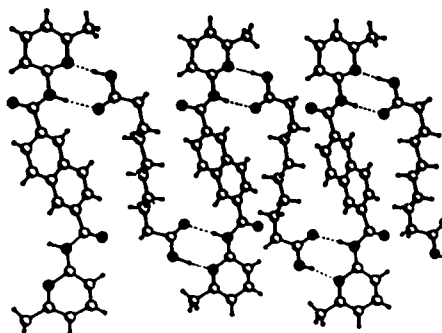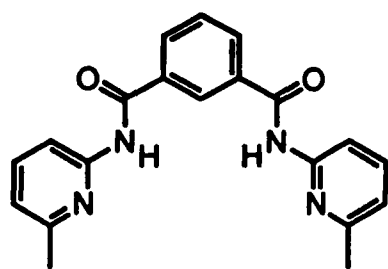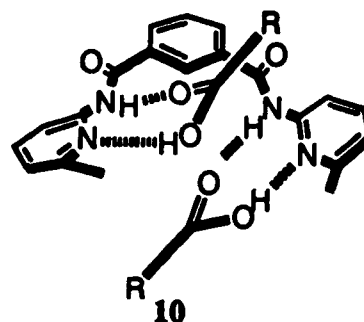


**Figure 4**



**Figure 5**

## 1.1.3 BASED ON HYDROGEN-BONDED HELICES

The bis-amide **3** formed from 2-aminopicoline and isophthalic acid is also expected to form polymeric aggregates with dicarboxylic acids of the types similar to that seen in Figures 7-10. However, when **3** takes a convergent conformation of the two aminopyridines (as shown) two carboxylic acids can only bind in a non-planar or helical manner (as shown in **5**). Propagation of this arrangement would lead to an extended, self-assembled helix. The complex between **3** and pimelic acid shows precisely this remarkable structure. A helix is formed

**4**     **10**

composed of alternating receptor-diacid components (Figure 6). Each molecule of **3** stacks parallel to the one above and the one below with an interplane distance of almost 8Å. A critical stabilizing feature in the crystal is the intercalation of the isophthaloyl rings of one helix into the space between the receptors in a second helix. This intercalation can only occur if there is sufficient distance between the isophthaloyl planes. The interplane distance will be controlled by the length of the diacid and shortening the diacid should eliminate the possibility of intercalation stabilization of the crystal.
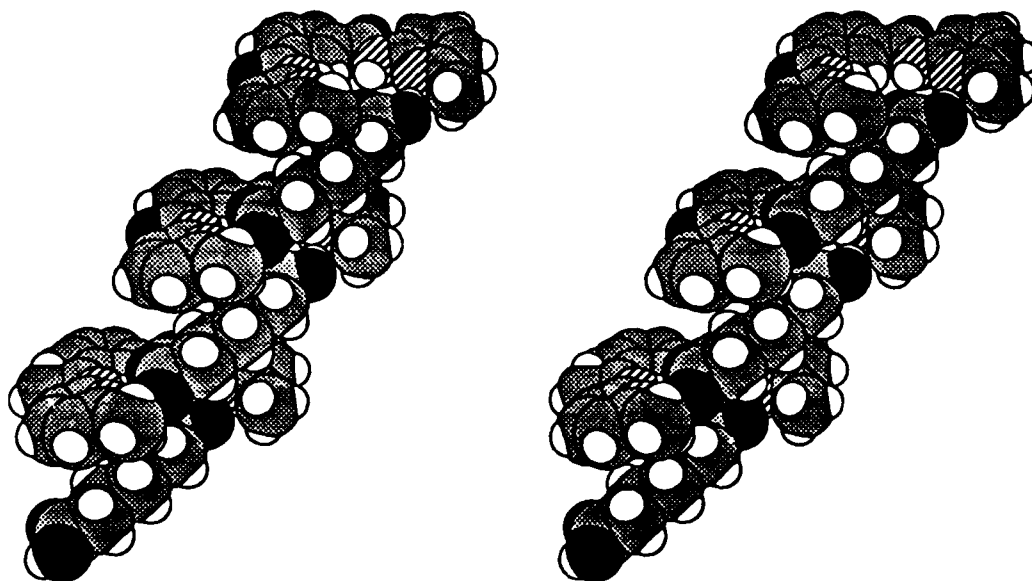


**Figure 6.** Stereoview of helical complex between **4** and pimelic acid.
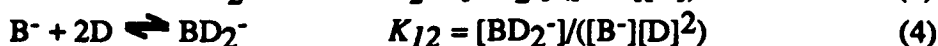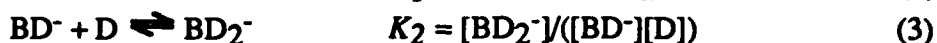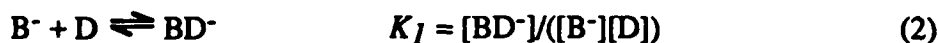
**Quantitative aspects of the physical properties of chemically responsive materials.** For this part of the study, large quantities of material were required. The synthetic products described above are quite valuable, so we sought an available material which would undergo an easily and reproducibly measurable physical change upon exposure to an agonist. Deuel had noted as early as 1948 that aqueous gels formed from the reaction between borate ion and poly(vinyl alcohol) were liquified by exposure to, for example, fructose but not by exposure to sucrose.[8] This is an ideal, if simple, model for a smart material.

Our eventual goal is the prediction of material properties based on the concentrations of the material's components and the concentration of the agonist. As a starting point, we wish to have a quantitative understanding of the properties of the material in the absence of agonist.

**Gel Chemistry.** Borax ($Na_2B_4O_7 \cdot 10H_2O$) is one component of the system. At low concentrations ($\leq 0.03$ M) borax hydrolyzes in water to give a boric acid/borate buffer:[9]

$$B(OH)_3 + 2H_2O \rightleftharpoons B(OH)_4^- + H_3O^+ \qquad pK_a = 9.2 \qquad (1)$$

Because our solutions are buffered at pH 10, the borate ion is the predominant species. Low molecular weight polyalcohols possessing a *cis*-1,2 or a *cis*-1,3 diol configuration (D) may bind borate, $B^-$, (or boric acid, BH) to form 1:1 complexes (monodiols, $BD^-$) and 2:1 polyol/borate complexes (didiols, $BD_2^-$).[8-15]

$$B^- + D \rightleftharpoons BD^- \qquad K_1 = [BD^-]/([B^-][D]) \qquad (2)$$

$$BD^- + D \rightleftharpoons BD_2^- \qquad K_2 = [BD_2^-]/([BD^-][D]) \qquad (3)$$

$$B^- + 2D \rightleftharpoons BD_2^- \qquad K_{12} = [BD_2^-]/([B^-][D]^2) \qquad (4)$$

Sugar-borate complex stability depends upon the configuration of the sugar (carbonyl or annular form), the number of hydroxyl groups on the sugar, and the presence of substituents on the sugar.[12] Finally, the addition of simple polyols to either boric acid or borax results in substantial pH reductions in unbuffered solutions.[10]

The interaction of polymeric polyols with the tetrahedral borate ion is not as well understood as is the case for low molecular weight polyols. The adjacent oxygens of the dominant 1,3-diol structure in PVA attach to boron to form monodiols and didiols (it is agreed by most[11,13,16,17] that PVA and other high molecular weight polysaccarides form only monodiols with boric acid).[8-11,13,16-20]

A total of 77 PVA-borate samples were prepared for viscosity measurements or boron determination. Of these 77, nine were gels, 39 were two-phase systems, and 29 were liquids. Compositions that yielded either a gel or two phases at the lowest boron concentration for each corresponding polymer concentration were plotted on a concentration matrix and the connecting lines were smoothed. Figure 7 shows the state of the resulting system as a function of boron concentration and diol concentration (polymer concentration is given in units of diol concentration because it is the diol that coordinates with borate). At low concentrations of each component, the solution is viscous. Gel formation is observed when a certain diol concentration is reached. At relatively high concentrations of boron, two-phases are formed; an elastic material separates from a relatively inviscid liquid. These materials will be studied in the future.

Figure 8 illustrates the viscosity as a function of component concentration. Viscosity measurements from twenty-three samples ranging in concentration from 0.129-0.258 M diol and from 0.840-2.38 mM boron were fit with a second order linear regression. The polynomial equation used to construct the graph is as follows:

$$\ln(\eta) = 4.63 - (23.83*D) - (4.28*B) + (21.69*D*B)$$
$$+ (41.81*D^2) + (0.50*B^2) \qquad (7)$$

where $\eta$ is the viscosity in cp, D is the diol concentration in M, and B is the boron concentration in mM (adjusted R-square value=0.939; standard error for the coefficient of D=10.5, the coefficient of B=1.42, the coefficient of D*B=3.37, the coefficient of
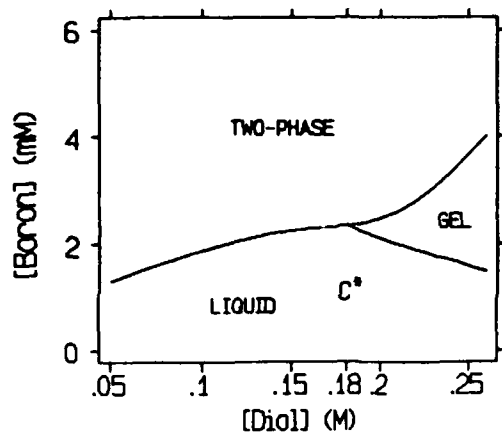
**Figure 7**    **Figure 8**

$D^2$=24.4, and the coefficient of $B^2$=0.378). The lower plateau corresponds to the gel region where viscosity is greater than 64 cp; the higher plateau corresponds to the two-phase region. The plateau heights are arbitrarily positioned along the ordinate. Viscosity increases significantly with boron concentration and diol concentration.

The determination of boron in equilibrium with the polymer in the dialysis experiments allows the equilibrium constants defined in equations 2 and 4 to be calculated. Substitution and rearrangement of the equation derived from simple mass balance gives

$$B_t = B_f + BD^- + BD_2^- = B_f + K_1*B_f*D + K_{12}*B_f*D^2$$
$$= B_f(1 + K_1*D + K_{12}*D^2) \tag{8}$$

so

$$B_t/B_f - 1 = B_b/B_f = K_1*D + K_{12}*D^2 \tag{9}$$

Here, $B_t$ is the total boron concentration and $B_f$ is the free boron concentration (free borate concentration plus free boric acid concentration). D is in excess. $K_1$ and $K_{12}$ were obtained by regressing the data on D and $D^2$. The value calculated for $K_1$ is 3.22 (standard error 1.83), and the value for $K_{12}$ is 2.13 (standard error 5.78); the adjusted R-square value is 0.716. Note that $K_{12}$, which governs crosslinking, is not significant. The simple mass balance situation may be inappropriate as will be explained in the discussion section.

We have developed a simple model that accomodates the well-understood small molecule formalism, but applies it to the polymer case in a way that is physically reasonable but distinct from the small molecule case.
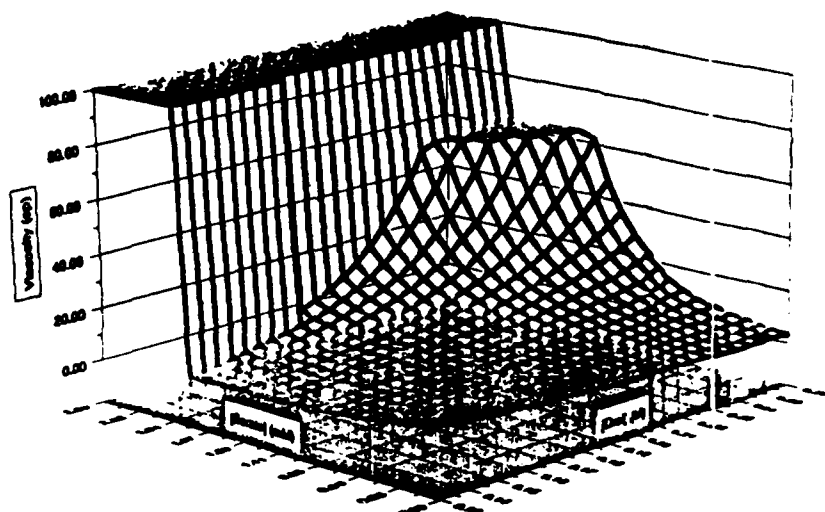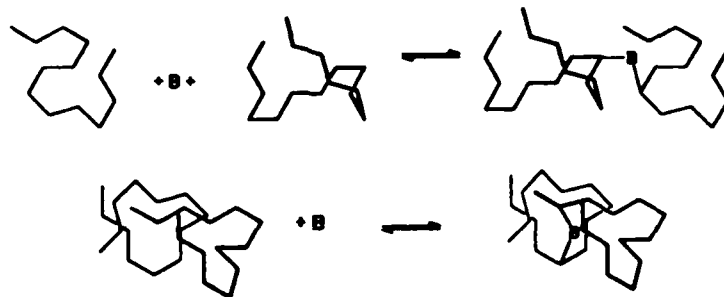
**Figure 9**
The essential feature of the model is that the reaction's left hand side represents two polymer chains that are separated by their equilibrium distance, which is dependent on the polymer concentration. When borate ion crosslinks the chains, they are at the same distance apart after crosslinking as they were before crosslinking (lower panel in Figure 9). In contrast, in the small molecule case, the equilibrium distance between the species being crosslinked decreases upon crosslinking (upper panel). Borate crosslinks polymer chains that are already close enough to be in contact. The polymer solution is preorganized, in a sense, to accept the borate crosslink.

The model bears a resemblance to micelle partitioning. The borate is viewed as partitioning among three volumes of solvent: polymer free solvent, solvent associated with single polymer chains, and solvent associated with regions in which the sphere of gyration of two polymer chains overlaps. The distribution coefficient depends only on the volumes of the three regions. Once the borate ion is in either of the regions containing a polymer chain, it can bind as a monodiol, as an intramolecular didiol, or as an intermolecular didiol. The binding depends on the polymer concentration in each region, but this is not related to the mass per volume concentration of the polymer, rather it is related to the solvent swollen molar volume of the polymer. The influence of polymer concentration arises through the change in the three volumes.

The behavior of the polymer as a ligand is quite different from the behavior of a small molecule. This contrast stems from the fact that the diols are connected on the polymer chain. Figures 10 and 11 illustrate the difference between the simple mass balance situation and the model. The concentration of monodiol is proportional to diol concentration in both cases, while didiol dependence on ligand concentration is shown only
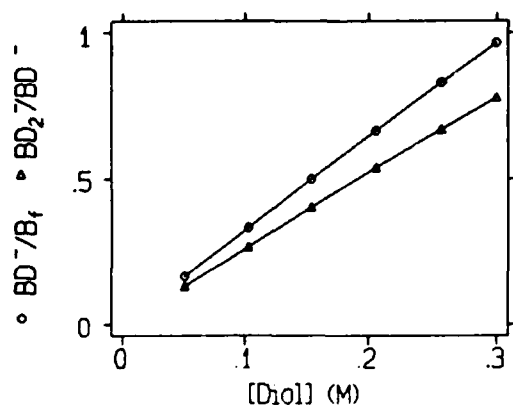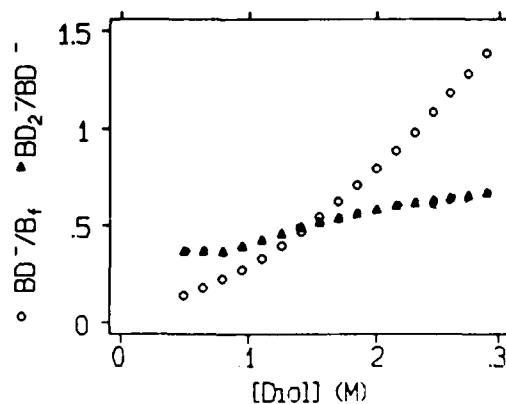


**Figure 10**



**Figure 11**

in the case represented in equations 2-4. The formation of 2:1 complexes as predicted by the model seems to follow the experimental behavior observed by Pezron *et al.*[21] The model shows that effects from local polymer concentration may be significant. In a dilute solution, it is highly probable that a 1:1 complex will react with a site on its own chain to form a 2:1 intramolecular crosslink. But in a more concentrated polymer solution where polymer/solvent sphere overlap occurs, the monodiol does not distinguish between a diol site on the same or another polymer chain; an increase in intermolecular complexes results. Thus, as Figure 11 shows, at low polymer concentrations $BD_2^-/BD^-$ appears constant and independent of the global diol concentration. $BD_2^-/BD^-$ increases at polymer concentrations usually greater than $C^*$.

Because we were able to determine free boron concentration experimentally, it is possible to compare these data with the predicted. Figure 12 shows that there is good agreement between theory and experiment.

Figure 13 shows the prediction of the gel point in the sol-gel transition from the theory. Excellent agreement is obtained.

Thus, we have established a simple, quantitative model for polymeric solutions that interact through a dimeric crosslinker.
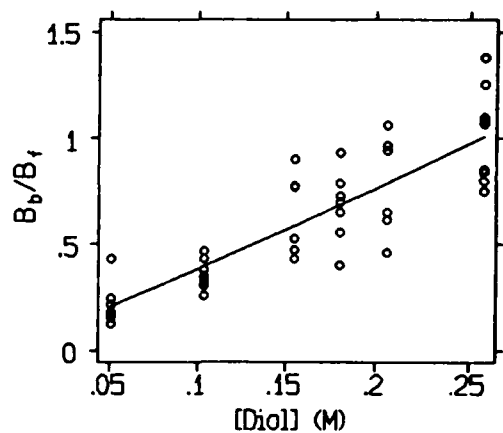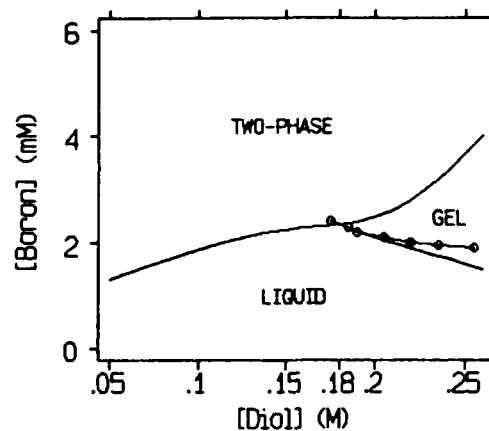


Figure 12



Figure 13

## REFERENCES

1. Etter, M. C. *Acc. Chem. Res.* **1990**, *23*, 120.
2. Leiserowitz, L., Hagler, A. T. *Proc. R. Soc. Lond. A.* **1983**, *388*, 133.
3. Leiserowitz, L., Tuval, M. *Acta Cryst.* **1978**, *B34*, 1230.
4. Zerkowski, J. A., Seto, C., Wierda, D. A., Whitesides, G. M. *J. Am. Chem. Soc.* **1990**, *111*, 9025.
5. Lehn, J. M., Mascal, M., DeCian, A., Fisher, J. *J. Chem. Soc. Chem. Commun.* **1990**, 479.
6. Geib, S. J., Hirst, S. C., Vicent, C., Hamilton, A. D. *J. Chem. Soc. Chem. Comm.* **1991**, 1283.
7. Hamilton, A. D. *Advances in Supramolecular Chemistry*, Vol. 1, Gokel, G. Ed. Jai Press, Greenwich, 1990, p1.
8. Deuel, H.; Neukom, H.; Weber, F. *Nature* **1948**, *161*, 96.
9. Casassa, E. Z.; Sarquis, A. M.; Van Dyke, C. H. *J. Chem. Ed.* ;**1986**, *63*, 57.
10. Nickerson, R. F. *J. Appl. Polym. Sci.* **1971**, *15*, 111.
11. Deuel, H.; Neukom, H. *Makromol. Chem.* **1949**, *3*, 13.
12. Hoffstetter-Kuhn, S.; Paulus, A.; Gassmann, E.; Widmer, H. M. *Anal. Chem.* **1991**, *63*, 1541.
13. Richetti, P. G.; Snyder, R. S. *Appl. Theor. Electrophor.* **1988**, *1*, 53.
14. Kankare, J. *J. Anal. Chem.* **1973**, *45*, 2050.
15. Knoeck, J.; Taylor, J. K. *Anal. Chem.* **1969**, *41*, 1730.
16. Ochiai, H.; Fujino, Y.; Tadokoro, Y.; Murakami, I. *Polym. Commun.* **1980**, *21*, 485.
17. Matsuzawa, S.; Yamaura, K.; Tanigami, T.; Somura, T.; Nakata, S. *Polymer* **1988**, *29*, 336.
18. Cheng, A. T. Y.; Rodriguez, F. *J. Appl. Polym. Sci.* **1981**, *26*, 3895.
19. Shibayama, M.; Sato, M.; Kimura, Y.; Fujiwara, H.; Nomura, S. *Polymer* **1988**, *29*, 336.
20. Maerker, J. M.; Sinton, S. W. *J. Rheology* **1986**, *30*, 77.
21. Pezron, E.; Leibler, L.; Ricard, A.; Lafuma, F.; Audebert, R.; *Macromolecules*, **1989**, *22*, 1169.