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Foreword

NASA-Langley's Computational Materials program began in October 1994. The interdisciplinary team representing NASA Centers, universities, and industry met formally for the first time in January 1995 at LaRC.

One year later, with some changes in personnel, the group assembled again, this time at The College of William and Mary, to review the technical progress that had been made and to identify future directions. The present document is a collection of the technical charts presented at that two-day workshop.

The concept of Computational Materials requires model development at size scales ranging from atomic dimensions to the macroscopic, and times ranging from picoseconds to weeks. The LaRC program therefore adopts a hierarchical approach, with careful attention paid to the links between disciplines. This collection of papers is presented in order of increasing scale, as follows:

<table>
<thead>
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<th>Workshop Participant</th>
<th>Discipline</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>G. D. Smith, U. Missouri-Columbia</td>
<td>Quantum/molecular mechanics</td>
<td>Subatomic to molecular</td>
</tr>
<tr>
<td>B. L. Farmer, U. Virginia</td>
<td>Molecular mechanics</td>
<td>Molecular</td>
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<tr>
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<td>E. J. Dawnkaski, College of William &amp; Mary</td>
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<td>Molecular assemblies</td>
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<td>R. A. Orwoll, College of William &amp; Mary</td>
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<td>T. Yost, J. Cantrell, NASA LaRC</td>
<td>Physics</td>
<td>Solids</td>
</tr>
<tr>
<td>W. W. Walsh</td>
<td>Chemistry; statistics</td>
<td>Molecular to continuum</td>
</tr>
<tr>
<td>W. G. Knauss, California Inst. of Tech.</td>
<td>Constitutive models</td>
<td>Continuum</td>
</tr>
<tr>
<td>T. S. Gates, NASA LaRC</td>
<td>Viscoplasticity</td>
<td>Micromechanics to macroscopic</td>
</tr>
</tbody>
</table>
Molecular Modeling of Polyimides

Grant D. Smith

Department of Chemical Engineering
University of Missouri-Columbia
Outline

- Ab initio quantum chemistry studies of a model imide
- Force field for a model imide
- Molecular dynamics simulations of a model imide
- Future work and directions
Structure of the model ether-imide
Bonded parameters

- From 6-31G** SCF optimized geometry

<table>
<thead>
<tr>
<th>Bond Stretch</th>
<th>Constrained (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C=O (carbonyl)(^a)</td>
<td>1.19</td>
</tr>
<tr>
<td>C-O (ether)</td>
<td>1.38</td>
</tr>
<tr>
<td>C-H</td>
<td>1.07</td>
</tr>
<tr>
<td>C=C</td>
<td>1.38</td>
</tr>
<tr>
<td>C(_i)-N</td>
<td>1.43</td>
</tr>
<tr>
<td>C- C(_i)</td>
<td>1.49</td>
</tr>
</tbody>
</table>

\(^a\) Bond length and force constant are determined from 6-31G** SCF optimized geometry.
## Bonded parameters, cont.

<table>
<thead>
<tr>
<th>Valence Bond</th>
<th>$E_{ij} = 0.5 k_{ij}(\theta_{ij} - \theta_{ij}^o)^2$</th>
<th>$k_{ij}$ (kcal/mol rad$^2$)</th>
<th>$\theta_{ij}^o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-C$_i$-N</td>
<td>144.</td>
<td>1.817</td>
<td></td>
</tr>
<tr>
<td>C-C-C$_i^b$</td>
<td>100.8</td>
<td>1.882</td>
<td></td>
</tr>
<tr>
<td>C-C-C$_i^c$</td>
<td>100.8</td>
<td>2.286</td>
<td></td>
</tr>
<tr>
<td>C$_i$-N-C$_i$</td>
<td>115.2</td>
<td>1.988</td>
<td></td>
</tr>
<tr>
<td>C-C$_i$-O</td>
<td>144.</td>
<td>2.253</td>
<td></td>
</tr>
<tr>
<td>C-C-C</td>
<td>144.</td>
<td>2.094</td>
<td></td>
</tr>
<tr>
<td>C-C-H</td>
<td>72.</td>
<td>2.094</td>
<td></td>
</tr>
<tr>
<td>C$_i$-N-C</td>
<td>115.2</td>
<td>2.148</td>
<td></td>
</tr>
<tr>
<td>C-O-C</td>
<td>148.6</td>
<td>2.072</td>
<td></td>
</tr>
<tr>
<td>C-C-O</td>
<td>100.8</td>
<td>2.094</td>
<td></td>
</tr>
<tr>
<td>N-C$_i$-O</td>
<td>100.8</td>
<td>2.1991</td>
<td></td>
</tr>
<tr>
<td>N-C-C</td>
<td>115.2</td>
<td>2.094</td>
<td></td>
</tr>
</tbody>
</table>
Torsional characteristics

6-31G+**
minimum = 52.4°
perp = 0.38 kcal/mol (9.8)
planar = 3.03 kcal/mol (4.7)

6-31G*
single = 2.5 kcal/mol (3.7)
double = 0.0 kcal/mol (1.2)
Partial atomic charges

- Charges were determined from electrostatic potential method--This method involves calculating the electrostatic potential for a grid of points around the molecule and best reproducing this with a distribution of partial atomic charges.
Partial atomic charges, cont.

- Carbon: q = +0.4892
- Carbon: q = -0.2201
- Carbon: q = +0.2839
- Carbon: q = +0.6817
- Carbon: q = -0.0856
- Ether oxygen: q = -0.5553
- Carbonyl oxygen: q = -0.5510
- Nitrogen: q = -0.4959
- Hydrogen: q = +0.1566
- Hydrogen: q = +0.1223
- Carbon: q = +0.1922
- Carbon: q = -0.0418
- Carbon: q = -0.2848
- Carbon: q = +0.5290

University of Missouri-Columbia

4 January
Nonbonded parameters

- Dispersion/repulsion parameters were mostly taken from our previous work.
- Extensive quantum chemistry and MD studies of benzene revealed the importance of including hydrogen atoms.
- Oxygen parameters were taken from our work with model ethers.
Nonbonded parameters, cont.

- Nitrogen Parameters were adjusted to match second virial coefficient data.

![Graph showing gas phase second virial coefficient vs. temperature (K) for trimethylamine.](image)
Nonbonded parameters

<table>
<thead>
<tr>
<th>Nonbonded Dispersion/Repulsion</th>
<th>( E_{ij} = A_{ij} \exp(-B_{ij}r_{ij}) - C_{ij}r_{ij}^6 )</th>
<th>( A_{ij} ) (kcal/mol)</th>
<th>( B_{ij} ) (Å)</th>
<th>( C_{ij} ) kcal/mol Å(^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-C</td>
<td></td>
<td>78988.</td>
<td>3.6</td>
<td>519.3</td>
</tr>
<tr>
<td>O-O</td>
<td></td>
<td>75845.</td>
<td>4.063</td>
<td>398.9</td>
</tr>
<tr>
<td>O-C</td>
<td></td>
<td>77400.5</td>
<td>3.8315</td>
<td>455.1</td>
</tr>
<tr>
<td>O-H</td>
<td></td>
<td>13448.4</td>
<td>3.902</td>
<td>99.1</td>
</tr>
<tr>
<td>O-N</td>
<td></td>
<td>67926.0</td>
<td>3.922</td>
<td>446.6</td>
</tr>
<tr>
<td>C-H</td>
<td></td>
<td>3888.0</td>
<td>3.415</td>
<td>124.416</td>
</tr>
<tr>
<td>C-N</td>
<td></td>
<td>69323.6</td>
<td>3.69</td>
<td>509.6</td>
</tr>
<tr>
<td>H-H</td>
<td></td>
<td>2384.6</td>
<td>3.74</td>
<td>24.624</td>
</tr>
<tr>
<td>H-N</td>
<td></td>
<td>28122.</td>
<td>4.252</td>
<td>127.7</td>
</tr>
<tr>
<td>N-N</td>
<td></td>
<td>60833.9</td>
<td>3.780</td>
<td>500.0</td>
</tr>
</tbody>
</table>
Out-of-plane deformation

- Parameters were taken from the empirical force field of Boyd

<table>
<thead>
<tr>
<th>Out-of-plane deformation</th>
<th>$E_{ijkl} = 0.5k_{ijkl}\delta^2$</th>
<th>$k_{ijkl}$ (kcal/mol rad$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-C*H-C</td>
<td></td>
<td>41.76</td>
</tr>
<tr>
<td>C-C*C$_i$-C</td>
<td></td>
<td>115.2</td>
</tr>
<tr>
<td>C-C$_i$*O-N</td>
<td></td>
<td>115.2</td>
</tr>
<tr>
<td>C$_i$-N*C-C$_i$</td>
<td></td>
<td>43.2</td>
</tr>
<tr>
<td>C-C*N-C</td>
<td></td>
<td>115.2</td>
</tr>
<tr>
<td>C-C*O-C</td>
<td></td>
<td>115.2</td>
</tr>
</tbody>
</table>
Molecular dynamics simulations

- 100 ether-imide molecules
- Ewald summation
- 5 fs time step (hydrogen atom positions constrained)
- Box = 36 Å
Density

- Experimental density measurements have been performed from 436 to 473 K.
- At 473 K, a constant volume simulation at experimental density yields a pressure of -700 atmospheres.
- At 473 K, a constant pressure simulation at 1 atmosphere yields a density about 4% greater than experiment.
Thermal expansion

- At 1 atmosphere, thermal expansion over the experimental temperature range is $7.7 \times 10^{-4}/K$
- The experimental value is $6.8 \times 10^{-4}/K$
Sensitivity of density to force field parameters

- The density is insensitive to intramolecular parameters
- The density does is not very sensitive to electrostatic interaction*
- We are investigating the sensitivity of the density to nonbonded parameters
Pair distribution functions

- We have begun looking for important intermolecular interactions by examining pair distribution functions
Pair distribution functions, cont.

![Graph showing x-H pair intermolecular distribution function against separation (Å) with curves for C-H, N-H, and O-H interactions.](image)
Pair distribution functions, cont.

![Graph showing pair distribution functions for C-H, N-H, and O-H separations.](image)

- **X-H dispersion/repulsion energy (kcal/mol)**
- **separation (Å)**

- C-H
- N-H
- O-H

*University of Missouri-Columbia* 4 January
Ongoing work

- PVT measurements of internal energy
- Force field parameterization for ketone-imide
- Fine-tuning of force fields
- MD simulation of model imide liquids
Key issues and future work

- Determine the most interesting chemical modifications to investigate
- Learn how to best interact with people further up the food chain-- including experimentalists and continuum models
- Apply techniques to interface, additives, etc.
Acknowledgments

- Dr. Richard Jaffe, NASA Ames Research Center
- Mr. Steven Shi
Table I
Quantum Chemistry Based Force Field for Ether-Imide

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy Function</th>
<th>Parameters (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bond Stretch</td>
<td>Constrained</td>
<td></td>
</tr>
<tr>
<td>C\textsubscript{i}=O (carbonyl)\textsuperscript{a}</td>
<td></td>
<td>1.19</td>
</tr>
<tr>
<td>C-O (ether)</td>
<td></td>
<td>1.38</td>
</tr>
<tr>
<td>C-H</td>
<td></td>
<td>1.07</td>
</tr>
<tr>
<td>C=C</td>
<td></td>
<td>1.38</td>
</tr>
<tr>
<td>Ci-N</td>
<td></td>
<td>1.43</td>
</tr>
<tr>
<td>C- C\textsubscript{i}</td>
<td></td>
<td>1.49</td>
</tr>
<tr>
<td>Valence Bend</td>
<td>E\textsubscript{ijk} = 0.5 k\textsubscript{ijk}(\theta\textsubscript{ijkl} - \theta\textsuperscript{o}\textsubscript{ijkl})\textsuperscript{2}</td>
<td>k\textsubscript{ijk} (kcal/mol rad\textsuperscript{2})</td>
</tr>
<tr>
<td>C-C\textsubscript{i}-N</td>
<td></td>
<td>144.0</td>
</tr>
<tr>
<td>C-C-C\textsubscript{i}\textsuperscript{b}</td>
<td></td>
<td>100.8</td>
</tr>
<tr>
<td>C-C-C\textsubscript{i}\textsuperscript{c}</td>
<td></td>
<td>100.8</td>
</tr>
<tr>
<td>C\textsubscript{i}-N-C\textsubscript{i}</td>
<td></td>
<td>115.2</td>
</tr>
<tr>
<td>C-C\textsubscript{i}-O</td>
<td></td>
<td>144.0</td>
</tr>
<tr>
<td>C-C-C</td>
<td></td>
<td>144.0</td>
</tr>
<tr>
<td>C-C-H</td>
<td></td>
<td>72.0</td>
</tr>
<tr>
<td>C\textsubscript{i}-N-C</td>
<td></td>
<td>115.2</td>
</tr>
<tr>
<td>C-O-C</td>
<td></td>
<td>148.6</td>
</tr>
<tr>
<td>C-C-O</td>
<td></td>
<td>100.8</td>
</tr>
<tr>
<td>N-C\textsubscript{i}-O</td>
<td></td>
<td>100.8</td>
</tr>
<tr>
<td>N-C-C</td>
<td></td>
<td>115.2</td>
</tr>
</tbody>
</table>
\[
Torsion \quad E_{ijkl} = 0.5[k^2_{ijkl} (1 - \cos(2\phi_{ijkl})) + k^4_{ijkl} (1 - \cos(4\phi_{ijkl}))]
\]

<table>
<thead>
<tr>
<th>Torsion</th>
<th>(k^2_{ijkl}) (kcal/mol)</th>
<th>(k^4_{ijkl})</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-C-C-C</td>
<td>25.92</td>
<td>0.00</td>
</tr>
<tr>
<td>C-C-C-H</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>H-C-C-H</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C\textsubscript{i}-C-C-C</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C\textsubscript{i}-C-C-H</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C\textsubscript{i}-C-C-C\textsubscript{i}</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>O-C\textsubscript{i}-C-C</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N-C\textsubscript{i}-C-C</td>
<td>0.72</td>
<td>0.00</td>
</tr>
<tr>
<td>C-N-C\textsubscript{i}-C</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>C-N-C\textsubscript{i}-O</td>
<td>14.40</td>
<td>0.00</td>
</tr>
<tr>
<td>C-C-O-C</td>
<td>0.86</td>
<td>0.00</td>
</tr>
<tr>
<td>C-C-C-O</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>H-C-C-O</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C-C\textsubscript{i}-C-O</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C\textsubscript{i}-N-C\textsubscript{i}-O</td>
<td>7.06</td>
<td>0.00</td>
</tr>
<tr>
<td>C-C-N-C\textsubscript{i}</td>
<td>1.20</td>
<td>0.26</td>
</tr>
<tr>
<td>N-C-C-C</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>N-C-C-H</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
The UVA (on-grounds) effort has focused on exploring the validity of the Tripos force field for computing the interactions between a graphite surface and a polyimide chain. Validation has proceeded along two paths.

The first validation path has involved comparison of calculations using the Tripos force field with the results of semiempirical molecular orbital and \textit{ab initio} calculations for pairs of molecules, e.g. methane, formaldehyde, and trimethyl amine with benzene. The comparisons have not been good. However, rather than point to a deficiency in the empirical (Tripos) force field, the results underscore the inability of the molecular orbital and \textit{ab initio} methods to properly represent dispersion interactions except when very extensive basis sets are employed. Thus the validation of the Tripos force field lies more correctly in the comparisons with experimental data than with the results with the more fundamental computational methods.

The second validation pathway involves calculations of the association between various small molecules (corresponding to representative fragments of polyimides) and a section of a graphitic surface (specifically, a coronene molecule) were made. These were compared with previous computational results based on more elegant treatments of the interaction potential developed to reproduce experimental data. Both the interaction energy \textit{versus} distance curve and the geometry of the minimum energy association calculated using the Tripos force field for benzene on graphite were in good agreement with the previous model and data. In addition,
comparisons of the experimental heats of adsorption of other molecular fragments with graphitic substrates were generally in good agreement with the calculated interaction energies.

Another aspect of the semiempirical molecular orbital and \textit{ab initio} calculations results however is both useful and interesting. Graphite, as a material, is electrically conductive. The effects of this conductivity on graphite's interactions with adsorbing material has apparently not been studied previously in the context of modern computational methods. (This neglect may arise in fact from the inability of molecular orbital calculations to provide a reasonable treatment of dispersion forces). A dipole in the vicinity of a conducting (metal) surface interacts electrostatically with an image dipole as well as through dispersion effects with the substrate atoms. The image interaction is about an order of magnitude smaller than the dispersive ones. This indicates that, overall, "summation of dispersion and repulsive energies" may indeed be a good approximation for computing the interaction energies of adsorbate molecules with graphite. At the same time, ignoring the image interactions may lead to underestimation of the role of the dipolar moieties of the polyimides on the interactions with the graphite substrate. The size of these effects will determine whether we will need to modify the potential function parameters to get a reasonable representation of the behavior of a polyimide on a graphite substrate. Since the interaction is electrostatic, the results of semiempirical molecular orbital and \textit{ab initio} calculations should be valid in spite of the inability of these methods to properly account for dispersion interactions.

The calculations to date indicate that the partial charges in the adsorbing molecule and those on the atoms of the "substrate" molecule (benzene, naphthalene, coronene) change to a small extent as the separation distance changes. As expected, the charges on the substrate atoms nearest the adsorbate change individually more than those at greater distances, drawing upon contributions from its own several neighbors. The perturbations in electron distribution extend out from the location of the adsorbate, but they are damped in magnitude.
Figure Captions and Annotations

Note:

Sybyl does molecular mechanics calculations using a classical description of the force field. Spartan does semiempirical molecular orbital (quantum mechanical) calculations.

1. Title

2. Polyimides of Interest

3. Energy (and partial atomic charge on methane hydrogen) versus separation distance between benzene and methane calculated using Spartan (semiempirical molecular orbital methods).

4. Energy (and partial atomic charge on fluorine) versus separation distance between benzene and perfluoromethane calculated using Spartan (semiempirical molecular orbital methods).

5. Energy (and partial atomic charge on nitrogen) versus separation distance between benzene and trimethyleamine calculated using Spartan (semiempirical molecular orbital methods).

6. Energy (and partial atomic charge on oxygen) versus separation distance between benzene and formaldehyde calculated using Spartan (semiempirical molecular orbital methods).

7. Charges on the formaldehyde carbon and oxygen and three of the benzene carbons as a function of distance between benzene and formaldehyde (calculated using Spartan semiempirical molecular orbital methods). These data show that the proximity of a polar (carbonyl) group perturbs the distribution of charges in the benzene molecule. What might be the effect of polar groups proximate to delocalized ring systems such as naphthalene, anthracene, coronene, and ultimately, graphite.

8. Charges on the formaldehyde carbon and oxygen and three of the naphthalene carbons in Ring 1 as a function of distance between naphthalene and formaldehyde (calculated using Spartan semiempirical molecular orbital methods). The formaldehyde molecule was centered over Ring 1 of the naphthalene molecule.

9. Charges on the formaldehyde carbon and oxygen and four of the naphthalene carbons in Ring 2 as a function of distance between naphthalene and formaldehyde (calculated using Spartan semiempirical molecular orbital methods). The formaldehyde molecule was centered over Ring 1 of the naphthalene molecule.

10. Charges on the formaldehyde carbon and oxygen and three of the anthracene carbons in Ring 1 as a function of distance between anthracene and formaldehyde (calculated using Spartan semiempirical molecular orbital methods). The formaldehyde molecule was centered over Ring 1 of the anthracene molecule.

11. Charges on the formaldehyde carbon and oxygen and three of the anthracene carbons in Ring 1 as a function of distance between anthracene and formaldehyde (calculated using Spartan semiempirical molecular orbital methods). The formaldehyde molecule was centered over Ring 2 of the anthracene molecule.
12. Charges on the formaldehyde carbon and oxygen and four of the anthracene carbons in Ring 2 as a function of distance between anthracene and formaldehyde (calculated using Spartan semiempirical molecular orbital methods). The formaldehyde molecule was centered over Ring 3 of the anthracene molecule.

*These data show that a polar group does induce charge redistribution in rings sharing delocalized electronic structure with the ring closest to the approaching polar functionality. The effect, not surprisingly, dies out with distance. This can be attributed (in part if not totally) to the fact that there is an increasing number of atoms to contribute decreasing amounts of charge (per atom).*

*How do molecular mechanics (Sybyl) results compare with semiempirical (Spartan) results. Specifically, how do the energy versus distance curves compare?*


15. Energy versus separation distance between coronene and formaldehyde calculated using Tripos force field and Sybyl for molecular mechanics.

16. Energy versus separation distance between coronene and formaldehyde calculated using Spartan semiempirical molecular orbital methods.

*The molecular mechanics results and semiempirical molecular orbital results are not in good agreement. Molecular mechanics methods compute van der Waals non-bonded interactions and Coulombic interactions as a matter of course. Semiempirical molecular orbital methods can account mainly for the Coulombic effects. Similarly, even ab initio methods cannot take into account non-bonded interactions (because they arise from electron correlation effects) unless prohibitively large, delocalized basis sets are used.*

*Comparisons with experimental data and other types of calculations in the literature might provide a better measure of the validity of the Tripos force field.*

17. Orthogonal views of a benzene molecule proximate to a coronene molecule (representing a section of a graphite sheet).

18. Relative energy as a function of distance between benzene and coronene (in the positions shown in the previous figure).

19. Title and figures from a paper reporting calculations (and comparisons with experimental data) for the absorption of benzene on graphite.

*The Sybyl results are in very nice agreement with the results in this paper, both in regard to the minimum energy orientation, the depth of the energy minimum, and the minimum energy separation distance.*
Molecular Mechanics
and
Molecular Dynamics

with applications to polyimides as piezoelectric and composite materials

B. L. Farmer

Materials Science and Engineering
University of Virginia
Piezoelectric Polyimides
Energy and Charge Versus Distance

Phen_Meth Molecule

Charge, Energy

Delta Energy
Charge H1

Distance (angstroms)
Energy and Charge Versus Distance

Phen\_CF4 Molecule

Charge, Energy

Distance (angstroms)
Energy and Charge Versus Distance

Delta Energy

Charge N14

Distance (angstroms)

Phen_mdnm Molecule

Energy, Energy

0 0.1 0.2 0.3 0.4 0.5 0.6

3.31 4.07 4.83 5.59 6.35 7.11 7.87
Energy and Charge Versus Distance

Phen-form Molecule

Charge, Energy

Delta Energy

Delta Charge O3

Distance (angstroms)
Charge Vs. Distance - Form and Benzene

Charge on atom

Distance (angstroms)
Charge Vs. Distance - Form and Nath

Charge on atom

Distance (angstroms)

Charge on atom vs. Distance (angstroms) graph showing different charge values for various atoms at different distances.
Charge on Carbon Atoms Versus Distance From Oxygen

Formaldehyde and Naphthalene

Charge on Carbon Atom

Distance from Oxygen

-0.20
-0.15
-0.10
-0.05

3.00  4.00  5.00  6.00  7.00  8.00  9.00
Charge Vs. Distance - Form and Anth

Ring 1

Charge on atom

Distance (angstroms)
Charge Vs. Distance - Form and Anth
Ring 2

Charge on atom

Distance (angstroms)
Charge Vs. Distance - Form and Anth
Ring 3

Charge on atom

Charge on atom

Distance (angstroms)
Energy Calculated by Spartan Versus Distance
Methane and Coronene Molecule
Energy Calculated by Sybyl and Spartan Versus Distance Formaldehyde and Corone Molecule
Energy Calculated by Sybyl with Charges Versus Distance
Formaldehyde and Coronene

Energy (Kcal/mol)

Distance (angstroms)
Change in Strain Energy Vs. Distance
Benzene and Coronene

Delta E (kcal/mol)

Distance (angstroms)
A molecular dynamics simulation of liquid benzene adsorbed on graphite

Reinhard Hentschke and Britta L. Schürmann
Max-Planck-Institut für Polymerforschung, Postfach 3148, D-6500 Mainz, Germany

Received 17 July 1991; accepted for publication 4 September 1991
EFFECT OF MOLECULAR WEIGHT ON PROPERTIES OF LARC™-SI

E. J. Siochi
Lockheed Martin Engineering and Sciences Company
Hampton, VA 23666
OUTLINE

• Introduction
• Objective
• Materials
• Characterization
  • Molecular Weight Determination
  • Thermal Analysis
  • Melt Viscosity
  • Density
  • Microhardness
  • Fracture Toughness
• Summary
INTRODUCTION

• Polyimides as materials of choice
  ✷ Excellent mechanical properties
  ✷ Excellent thermooxidative stability
  ✷ Good solvent resistance

• Tailoring of properties achieved using stoichiometric imbalance during synthesis

• Solubility of LARC™-SI allows systematic investigation of the relationship of molecular weight to properties of interest
MATERIAL

50/50

BPDA

ODPA

PA

H₂N

NH₂

3,4-ODA

NMP/Toluen

165°C

LaRC™-Si
Effect of Stoichiometric Offset on Intrinsic Viscosity

Intrinsic Viscosity (dl/g)

Stoichiometric Offset (%)
Effect of Stoichiometric Offset on Molecular Weight Averages

![Graph showing the effect of stoichiometric offset on molecular weight averages. The graph plots $M \times 10^{-4}$ (g/mol) against stoichiometric offset (%). The legend includes $M_n$, $M$, and $M_z^w$.](image-url)
Molecular Weight Characterization

<table>
<thead>
<tr>
<th>Sample Offset (%)</th>
<th>$M_n$ (g/mol)</th>
<th>Theoretical $M_n$ (g/mol)</th>
<th>$M_w$ (g/mol)</th>
<th>$M_z$ (g/mol)</th>
<th>$M_v$ (g/mol)</th>
<th>Intrinsic Viscosity (dL/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11450</td>
<td>$\infty$</td>
<td>58900</td>
<td>107350</td>
<td>43035</td>
<td>0.578</td>
</tr>
<tr>
<td>1</td>
<td>11180</td>
<td>44819</td>
<td>51070</td>
<td>87130</td>
<td>37530</td>
<td>0.600</td>
</tr>
<tr>
<td>2</td>
<td>13770</td>
<td>22297</td>
<td>41100</td>
<td>75703</td>
<td>31675</td>
<td>0.470</td>
</tr>
<tr>
<td>3</td>
<td>10560</td>
<td>14789</td>
<td>24290</td>
<td>43955</td>
<td>19170</td>
<td>0.356</td>
</tr>
<tr>
<td>4</td>
<td>10405</td>
<td>11036</td>
<td>21180</td>
<td>39110</td>
<td>17155</td>
<td>0.326</td>
</tr>
<tr>
<td>5</td>
<td>8882</td>
<td>8784</td>
<td>15880</td>
<td>26935</td>
<td>13690</td>
<td>0.273</td>
</tr>
</tbody>
</table>
Effect of Molecular Weight on the Properties of a Soluble Polyimide

OBJECTIVE

- Quantitative understanding of how molecular weight characteristics influence selected properties of an advanced polymer matrix resin

APPROACH

- Synthesize a series of soluble polyimides having controlled molecular weights

- Characterize polymer series with methods of analysis routinely practised by Composites and Polymers Branch

- Find relationships between physical properties of polymers and molecular weights
Differential Scanning Calorimetry

4% Offset

dT/dt = 10°C/min
Atmosphere = N₂

Heat Flow (mW)

Temperature (°C)
### Thermal Characterization

<table>
<thead>
<tr>
<th>Sample Offset (%)</th>
<th>Tg from DMA (°C)</th>
<th>Tg from DSC (°C)</th>
<th>5% Weight Loss (°C)</th>
<th>Weight Change at 177°C After 100 Hours (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>253</td>
<td>239</td>
<td>498</td>
<td>-0.2</td>
</tr>
<tr>
<td>1</td>
<td>258</td>
<td>248</td>
<td>523</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>248</td>
<td>467</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>249</td>
<td>242</td>
<td>527</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>246</td>
<td>230</td>
<td>505</td>
<td>-0.2</td>
</tr>
<tr>
<td>5</td>
<td>--</td>
<td>231</td>
<td>520</td>
<td>0</td>
</tr>
</tbody>
</table>
Melt Viscosity Calculation

$$\eta = \frac{\tau_w}{\dot{\gamma}_w}$$
$$\tau_w = \frac{RP}{2l}$$
$$\dot{\gamma}_w = \frac{4Q}{\pi R^3}$$

$$\eta = \text{Melt Viscosity}$$
$$Q = \text{Volume Flow Rate}$$
$$R = \text{Capillary Radius}$$
$$P = \text{Pressure Drop}$$
$$l = \text{Capillary Length}$$
Microhardness Determination

Front View
(172° 30'')

Side View
(130°)

KHN = P/AP
KHN = Knoop Hardness
P = Load (kg)
AP = Area of the Impression
Density Determination Apparatus

\[ \rho_2 = \frac{A}{P} \cdot \rho_o \]

\( \rho_2 \) = Density of Solid Body
\( A \) = Weight of Solid Body in Air
\( P \) = Buoyancy of Solid Body in Test Liquid
\( \rho_o \) = Density of Test Liquid at a Given Temperature
## Density of LaRC™-SI

<table>
<thead>
<tr>
<th>Stoichiometric Offset (%)</th>
<th>Density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.365</td>
</tr>
<tr>
<td>1</td>
<td>1.360</td>
</tr>
<tr>
<td>2</td>
<td>1.361</td>
</tr>
<tr>
<td>3</td>
<td>1.359</td>
</tr>
<tr>
<td>4</td>
<td>1.359</td>
</tr>
</tbody>
</table>
Compact Tension Configuration for Fracture Toughness

\[ K_Q = \frac{P_Q}{BW^{1/2}} \cdot f(a/W) \]

- \( K_Q \) = Fracture Toughness
- \( P_Q \) = Maximum Load
- \( B \) = Specimen Thickness
- \( W \) = Specimen Width
- \( a \) = Crack Length
Effect of Stoichiometric Imbalance on Molecular Weight Distribution

Weight Fraction (%)

Log M

0% Offset
1% Offset
2% Offset
3% Offset
4% Offset
5% Offset
Effect of Molecular Weight on Fracture Toughness

\[ K_{IC} \text{ (MPa}\sqrt{m}) \]

\[ M_n \times 10^{-3} \text{ (g/mol)} \]

\[ X = A - B/M_n \]

- 4%
- 3%
SEM Photomicrographs of LaRC™-SI Fracture Surfaces

0% Offset

1% Offset

2% Offset

3% Offset

4% Offset

5% Offset
SUMMARY

- Controlled molecular weight soluble polyimides were synthesized.

- Stoichiometric offsets were reflected in the higher moments of the molecular weight distribution.

- Glass transition temperatures ranged from 230-248°C for 0-5% offset in stoichiometry.

- Scatter in TGA data showed no clear dependence of thermooxidative stability on molecular weight.

- Melt viscosity varied logarithmically with $M_w$.

- Density was not affected by molecular weight.

- Hardness varied linearly with $M_n$.

- Fracture toughness decreased sharply for materials with greater than 3% offset in stoichiometry.
FUTURE WORK

- Moldings have been made for other members of the NASA LaRC Computational Materials group.

- A series of phenylethynyl terminated LARCTM-Si is being synthesized to examine the effect of crosslinking on properties.
Molecular Modeling of Novel Piezoelectric Polyimides

by

J.A. Young and B.L. Farmer
Department of Materials Science and Engineering
University of Virginia
Charlottesville, VA

and

J.A. Hinkley
NASA Langley Research Center
Hampton, VA
PURPOSE

Computational chemistry techniques are used to model the large piezoelectric responses seen in novel high temperature polyimides. Molecular orbital calculations and molecular dynamics on two dimensional systems are used to investigate the nature of the piezoelectric response by characterizing the underlying molecular physics of the process. This information will then be used to propose mechanisms for enhancing the response by maximizing the polymers ability to assume conformations that enhance the materials polarization and its electrical response to stress.
PIEZOELECTRICITY

Materials which electrically responded to mechanical deformations (or visa versa) are said to be piezoelectric. Piezoelectric materials are formed from polar amorphous polymers by:

1) inducing orientation polarization. Apply an electric field, $E_p$, at a temperature, $T_p$, near $T_g$ to induce a remnant polarization, $P_r$ in the material.
2) characterize the electrical response (electrical current, D or electric field, E) of the material as a function of mechanical deformation, T.

\[ d = \frac{\delta D}{\delta T} \bigg|_E \] for closed circuit

or

\[ g = \frac{\delta E}{\delta T} \bigg|_D \] for open circuit
# MOLECULES OF INTEREST

<table>
<thead>
<tr>
<th>Polyimide Structure</th>
<th>Tg (K)</th>
<th>$g_{33}$ (Vm/N) at 353 K *</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Polyimide Structure 1" /></td>
<td>449</td>
<td>8.0</td>
</tr>
<tr>
<td><img src="image2" alt="Polyimide Structure 2" /></td>
<td>453</td>
<td>8.5</td>
</tr>
<tr>
<td><img src="image3" alt="Polyimide Structure 3" /></td>
<td>493</td>
<td>13.5</td>
</tr>
</tbody>
</table>

*Note: for PVF$_2$, $g_{33} = 0.2$ Vm/N at 353 K.*

---

PARAMETERIZATION

Prior to being able to carry out force field based calculations (molecular mechanics or molecular dynamics) the proper force field parameters must be obtained.

* Compare the potential energy surfaces of components of the polyimide backbone calculated via quantum mechanical methods and molecular mechanics with various force fields.

* Modification of BIOSYM's CFF91 force field reproduced the MOPAC / Ab Initio surfaces.
**MOPAC with the AM1 parameterization was used to generate partial atomic charges for the polyimides. Charge neutral groups were then formed while maintaining the original dipole moment.**
GENERATE AMORPHOUS CELL

Construction of a two dimensionally periodic amorphous box was done via the Amorphous Cell module in BIOSYM.

★ Build a low density (0.2 g/cm$^3$) five-mer polyimide cell.

★ Run high pressure (5000 bar) molecular dynamics until system reaches experimental density (1.34 g/cm$^3$).

★ Merge plates of tightly packed 'dummy atoms' to x-y faces of polymer cell. Placing charges on these plates will simulate the electric poling field.
View of parent box (red) within the systems periodic boundaries.
The parent cell containing a five-mer polyimide and plating atoms.
Molecular dynamics was done to obtain a starting configuration.

- The plates of dummy atoms were fixed in space.
- Group based non-bonded cutoffs of 9.5 Å for the Lennard Jones contribution and 17.5Å (the distance between the plates) for the Coulombic terms were used.

The total pair distribution function is the probability of finding any two atoms at a distance $r$ apart relative to the expected probability for a homogeneous system with random atoms.

$$g(r)=(N_f*V) / (N*4*π*r^2*dr)$$

- The peaks are associated with specific covalent bonds and interatomic distances along the rings. The absence of peaks at long distances, $r>5Å$, indicates the lack of long range order in the system.
Pair Distribution Function

Chart 1
POLE MATERIAL

Molecular dynamics was used to simulate the poling of the material.

Following Experimental Variables

A poling field of 150 MV/m ( +/- 0.013 e^-/plating atom) was placed on the system at $T_p=500K$.

50ps for dynamics were run at 500K.

System was cooled to 300 K in 10 K steps each lasting 10 ps. Once at 300 K the system was simulated for 50 ps.
A small polarization of 0.006 C/m² was obtained when using experimental parameters.
**Collapse Time Scale**

มวล Dipole relaxation times are of the order of micro-seconds. Molecular dynamics calculations cover only the pico-second / nano-second range.

มวล Collapse the time scale of the polarization process into the pico-second range.

❖ Translate time and temperature.

\[ \tau = \left[ \frac{3\varepsilon_s}{(2\varepsilon_s + \varepsilon_\alpha)} \right] \left[ \frac{h}{kT} \right] \left[ \exp(\Delta F/kT) \right] \]

❖ Maintain the population densities of the dipoles.

\[ mE / kT \]
Collapsed parameters for dynamics simulation.

- $T_p = 2100$ K
- $E_p = 700$ MV/m (i.e. +/- 0.052 e$^-$/plating atom)

The calculated polarization of 0.02 C/m$^2$ is obtained when using the parameters obtained after collapsing the time scale.
Dipole Reorientation

Chart 1

Dipole Moment Cell (d)

Time (ps)

X Component

Y Component

Z Component

0 5 10 15 20 25 30

0 5 10 15 20 25 30
A polarization of 0.02C/m² was obtained when using the collapsed time scale parameters
CONCLUSIONS

- Force field parameters were corrected then validated to give agreement with quantum mechanical results.

- The bulk polyimide was modeled by creating a two dimensionally periodic amorphous cell.

- Computer simulation techniques have been developed to model the poling of amorphous polyimides.

  - High temperatures and high poling fields were used to account for the long relaxation times.
  - Polarizations of 0.02 C/m² were calculated for the polyimide.
FUTURE WORK

למת Construct and simulate several initial configurations to achieve better statistics.

_multiply Calculate piezoelectric response by monitoring dipole orientation during constant stress dynamics.

Multiply Analyze molecular motions which occur as a result of the poling and deformation processes.

Multiply Propose novel polyimide structures and rank their piezoelectric responses, calculation of absolute values is not the focus of this research.
ACKNOWLEDGMENTS

We would like to thank the following:

NASA Langley the sponsor of this project:
The Graduate Student Researchers Program

Joycelyn O. Simpson of NASA Langley Research Center,
Hampton, VA for providing the experimental input.

Fiona Case of BIOSYM Technologies, San Diego, CA for
providing software support.
Monte Carlo Simulation of a Polyimide Melt

http://pooh.chem.wm.edu/~ejd/research/meet1/
Monte Carlo

- Bridge the gap between sub-microscopic and macroscopic
  - Retain knowledge and detail of sub-microscopic system
  - Determine macroscopic quantities

- Larger system sizes

- Faster simulations (larger time frame available)
Types of Monte Carlo

- Slithering Snake
- Kink-Jump
- Bond Fluctuation
Slithering Snake Monte Carlo

- One move type
- Unrealistic on local scale

Kink Jump Monte Carlo

## Bond Fluctuation vs Kink-Jump

<table>
<thead>
<tr>
<th>BFMC</th>
<th>KJMC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ADVANTAGES</strong></td>
<td></td>
</tr>
<tr>
<td>□ Computationally more efficient</td>
<td>□ Longer move length</td>
</tr>
<tr>
<td>□ One move type</td>
<td>□ Faster equilibration in less dense systems</td>
</tr>
<tr>
<td>□ Acceptance probability higher</td>
<td></td>
</tr>
<tr>
<td>□ Faster equilibration in dense systems</td>
<td></td>
</tr>
<tr>
<td><strong>DISADVANTAGES</strong></td>
<td></td>
</tr>
<tr>
<td>□ Short move length</td>
<td>□ Three types of motion</td>
</tr>
<tr>
<td>□ More steps to reach equilibrium</td>
<td>□ Lower acceptance probabilities</td>
</tr>
<tr>
<td>□ Slower equilibration time in less dense systems</td>
<td>□ Computationally less efficient</td>
</tr>
<tr>
<td></td>
<td>□ Slower equilibration time in dense systems</td>
</tr>
</tbody>
</table>
**Bond Fluctuation Monte Carlo:**

**The details**

<table>
<thead>
<tr>
<th>Allowed motion:</th>
<th>This yields 108 Bonds with 5 different bond lengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathbf{P}(1,0,0) )</td>
<td>( b = 4^{1/2}, 5^{1/2}, 6^{1/2}, 9^{1/2}, 10^{1/2} )</td>
</tr>
<tr>
<td>Allowed bond vectors:</td>
<td>Two successive bonds may have up to 87 different angles over the interval [0-180] degrees.</td>
</tr>
<tr>
<td>Union of:</td>
<td></td>
</tr>
<tr>
<td>( \mathbf{p}(2,0,0), \mathbf{p}(2,1,0), )</td>
<td></td>
</tr>
<tr>
<td>( \mathbf{p}(2,1,1), \mathbf{p}(2,2,1), )</td>
<td></td>
</tr>
<tr>
<td>( \mathbf{p}(3,0,0), \mathbf{p}(3,1,0) )</td>
<td></td>
</tr>
</tbody>
</table>
Summary of Restrictions

Excluded Volume:

The surrounding 26 grid locations must be vacant.

Bond Vector:

Set of allowed bond vectors prevents intrachain crossing.

Allows only 5 bond lengths.

Allows only 87 bond angles.

What About Energetics?

Metropolis Transition Probability: \( w = \min[1, e^{(-E/kT)}] \)
Energy Restrictions

- **Psuedo Bond Length**
  
  No Restrictions

- **Bond Angles**
  
  Restricted by bond bend stiffness (calculated via biosym)

- **"Long Range Torsions"**
  
  Calculate Energies for torsions and restrict accordingly

- **Inter-chain interactions:**
  
  Not accounted for as of yet
What is LARC-IA?

Go to Page Seven

LARC-IA

http://pooh.chem.wm.edu/...esearch/meet1/page6.html
C-O-C Bond Bend for di-phthalimide ether

http://pooh.chem.wm.edu/...search/meet1/page14.html

Energy (Kcal)

C-O-C Bond Angle (Degrees)

43.5
46.5
49.5
52.5

100 110 120 130 140

01/05/96 10:55:25
Bond Fluctuation representation of LARC-IA
Set up System

Update Vectors & Grid

Move Sub-unit

Select Sub-unit (randomly)

Select Random Move Direction

Allow by excluded volume?

Yes

No

Allow by bond vector?

Yes

No

Allow by energetics?

Yes

No

generate random number
Four Larc-IA Chains
3 monomers each
18 subunits each
Four Larc-lA Chains
3 monomers each
18 subunits each
Six sub-units of one monomer of LARC-IA
4 Chains of Larc-lA
(6 monomers, 6 subunits)
after 50,000 MC steps
Cross Linking

- Allow only end cross linking.
- Chain Ends will be allowed to cross link with other chain ends.
- All restrictions must still be met.
- Cross link kinetics as function of MC step (and also Time?).
Equation of State Measurements: Thermal Pressure Coefficient of an Imide-Ketone Model Compound

Robert Orwoll and Rachel Ward
Department of Chemistry
College of William and Mary
Williamsburg, VA 23187
\[
\frac{\Delta E_{\text{vap}}}{V_{\text{iq}}} = \text{Cohesive Energy Density}
\]

\[
p = T \left( \frac{\partial p}{\partial T} \right)_V - \left( \frac{\partial E}{\partial V} \right)_T
\]

\[
\text{Internal Pressure} = \left( \frac{\partial E}{\partial V} \right)_T = T \left( \frac{\partial p}{\partial T} \right)_V - p
\]

\[
\left( \frac{\partial p}{\partial T} \right)_V = \frac{1}{V} \left( \frac{\partial V}{\partial V} \right)_P - \frac{1}{V} \left( \frac{\partial V}{\partial p} \right)_T
\]

\[
\text{Thermal Pressure Coefficient} = \gamma_V = \frac{\alpha_p}{\kappa_T}
\]
"CONSTANT" VOLUME CELL FOR MEASURING THE THERMAL PRESSURE COEFFICIENT
MOLECULAR STRUCTURES FOR THE MODEL ETHER-IMIDE (TOP) AND KETONE-IMIDE (BOTTOM)
Pressure vs Temperature
of a Model Imide-Ketone

RESULTS FOR THE KETONE-IMIDE (BEFORE CORRECTION FOR THE EXPANSION AND COMPRESSION OF THE MERCURY AND GLASS)

Slope = (dp/dt)v
= 173.483 psi/°C
Comparison with Other Amorphous Compounds

<table>
<thead>
<tr>
<th>Compound</th>
<th>$(\partial E/\partial V)_T$, J/cm³</th>
<th>Temp, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$-octane</td>
<td>265</td>
<td>25</td>
</tr>
<tr>
<td>benzene</td>
<td>379</td>
<td>25</td>
</tr>
<tr>
<td>cyclohexanone</td>
<td>413</td>
<td>25</td>
</tr>
<tr>
<td>poly(dimethyl siloxane)</td>
<td>145</td>
<td>180</td>
</tr>
<tr>
<td>polyethylene</td>
<td>275</td>
<td>180</td>
</tr>
<tr>
<td>polyethylene oxide</td>
<td>433</td>
<td>100</td>
</tr>
<tr>
<td>imide ketone</td>
<td>440</td>
<td>186</td>
</tr>
</tbody>
</table>

p-V-T Results to Date

<table>
<thead>
<tr>
<th>Model Cmpd</th>
<th>CTE = $(1/V)(\partial V/\partial T)_P$, K⁻¹</th>
<th>$(\partial E/\partial V)_T$, J/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>imide ketone</td>
<td>$6.59 \times 10^{-4}$ ($\pm 3 \times 10^{-6}$)</td>
<td>$440 \pm 10$</td>
</tr>
<tr>
<td>imide ether</td>
<td>$6.83 \times 10^{-4}$ ($\pm 3 \times 10^{-6}$)</td>
<td>next measurement</td>
</tr>
</tbody>
</table>
Mechanical Properties from Acoustical Measurements on LaRC-SI

Tom Yost and John Cantrell
Outline

1. Relationship between acoustical measurements and mechanical properties. The application of $F=ma$ to the material, the results from which elastic constants and engineering moduli can be determined.

2. Thermodynamic definitions for major concepts in above.

3. Schematic view of ultrasonic measurement system.

4. Measurements to determine the effects of molecular weight on engineering moduli, and discussion.

5. Future Plans
1. Relationship between Acoustical Measurements and Moduli
Relationship between Acoustical Measurements and Mechanical Properties

- We begin with the force acting on a small segment of isotropic material. We apply $F=ma$ to the segment.
- This leads to the equation

$$
\frac{\partial \sigma}{\partial x_1} s_1 + \frac{\partial \sigma}{\partial x_2} s_2 + \frac{\partial \sigma}{\partial x_3} s_3 = F_s
$$

where
- $\sigma$ is the stress
- $s_k$ is the stress acting on the segment
- $u$ is the particle displacement
- $\rho$ is the density
- $x_k$ is the particle location (at rest)
Hooke's Law

- For the general case Hooke's Law can be expressed as

\[ \sigma_{sk} = c_{sklm} e_{lm} \]

where the \( c_{sklm} \) are the second-order elastic constants.

- The strain is expressed as

\[ e_{lm} = \frac{1}{2} \left( \frac{\partial u|_l}{\partial x_m} + \frac{\partial u|m}{\partial x_l} + \frac{\partial u_p}{\partial x_m} \frac{\partial u_p}{\partial x_l} \right) \]
The Wave Equation

- Combining Eq. 1 with Hooke's Law we obtain

\[ \rho \ddot{u}_s = c_{sklm} \frac{\partial^2 u_m}{\partial x_k \partial x_l} \]

- Consider a plane harmonic travelling wave of the form

\[ u_s = A_s e^{i(k \cdot x + \omega t)} \]

where \( A_s \) are the amplitudes of the displacement components.

- \( k_j \) are the components of the wave vector
  (magnitude of wave vector = \( 2\pi/\lambda \))

- \( \omega \) is the angular frequency of the wave
  (= \( 2\pi f \), \( f \) is frequency)

- \( i \) is the square root of \(-1\)
Wave Speed and Elastic Constants

- We substitute the expression for the wave into the equation of motion and obtain

\[ \rho \omega^2 s = c_{sklm} k^k l^l u^m \]

which gives

\[ (\rho \omega^2 \delta_{sm} - c_{sklm} k^k l^l) u^m = 0 \]

and finally to the relationship between the elastic constants and the wave velocity

\[ |c_{sklm} n^k l^l - \rho c^2 \delta_{sm}| = 0 \]
Elastic Constants and Engineering Moduli

Once the elastic constants are determined, the engineering moduli (Young's Modulus, $E$, Poisson's contraction, $\mu$, and bulk modulus, $K$) can be determined. For an isotropic material with Lamé constants, $\lambda$ and $\mu$, we have:

\[ E = \frac{G(3\lambda + 2G)}{\lambda + G} \]

\[ \mu = \frac{\lambda}{2(\lambda + G)} \]

\[ K = \lambda + \frac{2}{3}G \]

where

\[ \lambda = c_{1122} = c_{1133} = c_{2233} \]

\[ G = \frac{1}{2}(c_{1111} - c_{1122}) \]

\[ = c_{2323} = c_{3131} = c_{1212} \]
2. Thermodynamic Basis
Thermodynamic Definitions of Elastic Constants

- The elastic constants can also be defined in terms of thermodynamic variables

\[
S_{sklm} = \rho \frac{\partial^2 U}{\partial \varepsilon_s \partial \varepsilon_{lm}} \quad \text{(adiabatic conditions)}
\]

\[
0 \text{ stress}
\]

where \( U \) is the internal energy

- These are the elastic constants used in this study
Thermodynamic Definitions of Stresses and Strains

We start with the second law of thermodynamics and write the differential work in terms of stress and strain. This gives

\[
dU = \sigma_{ik} d\varepsilon_{ik} + T dS
\]

The Helmholtz free energy is given as

\[
F = U - TS
\]

\[
dF = \sigma_{ik} d\varepsilon_{ik} - S dT
\]

The Gibbs free energy is given as

\[
\Phi = F - \sigma_{ik} \varepsilon_{ik}
\]

\[
d\Phi = -S dT - \varepsilon_{ik} d\sigma_{ik}
\]

Hence

\[
\sigma_{ik} = \left( \frac{\partial U}{\partial \varepsilon_{ik}} \right) S = \left( \frac{\partial F}{\partial \varepsilon_{ik}} \right) T \quad \varepsilon_{ik} = -\left( \frac{\partial \Phi}{\partial \sigma_{ik}} \right) T
\]
Thermodynamic Definition of Elastic Constants

\[ c_{ijkl} = \rho_0 \left( \frac{\partial^2 U}{\partial \eta_{ij} \partial \eta_{kl}} \right) \]

The elastic constants used in this study are isentropic elastic constants.
3. Overview of Ultrasonic Measurements
Viscoelastic Materials and Ultrasonic Measurements (Linear Moduli)

Before measurement the sample thickness is determined. The oscilloscope measures the transit time. From these two measurements the sound velocity can be determined.

This ultrasonic technique measures the unrelaxed second-order moduli of the LaRC-SI sample.
4. Sample Set Preparation and Measurements

Five sample sets were prepared from each of the molecular weight offset stocks. Each set consisted of one sample from each molecular weight offset. Every sample was lapped and polished so that the surfaces were flat (to one band of green light) and parallel to better than 20 Arc sec. The following measurements include:

- Density measurements on 5 sample Sets
- Ultrasonic Wave Velocities (Set 5a and Averages)
- Moduli of LaRC-SI at room temperature (Set 5a and Averages)
4. Summary of Measurements
Graphs show compressional and shear velocities as well as moduli calculated from them. Enclosed is a chart of measured densities.
Ultrasonic Shear Wave Velocity in LaRC-SI

Sample Set 5a
0° Shear

Legend

--- 25%, 75%
[Box] 5%, 95%
##±## Mean±SD

Shear Wave Velocity (m/s)

1092.6±2
1098.8±1
1092.2±2
1094.9±2
1094.1±2

Molecular Weight Offset
Ultrasonic Shear Wave Velocity in LaRC-SI

Legend

- Median
---- 25%, 75%
[Box] 5%, 95%
###±# Mean±SD

Sample Set 5a
90° Shear

Shear Wave Velocity (m/s)

Molecular Weight Offset

1094.5±1

1098.0±1

1092.7±2

1096.5±1

1095.5±1
Isentropic Shear Wave Modulus in LaRC-SI

Legend
- - - - - Median
-----25%, 75%
[Box] 5%, 95%
###±# Mean±SD

Sample Set 5a
0° Shear

Shear Wave Modulus (GPa)

Molecular Weight Offset

1.5 1.55 1.6 1.65 1.7 1.75 1.8 1.85

1% 2% 3% 4% 5%
Isentropic Shear Wave Modulus in LaRC-SI

Legend

Median

25%, 75%

[Box] 5%, 95%

Mean±SD

Sample Set 5a

90° Shear

Shear Wave Modulus (GPa)

Molecular Weight Offset

1.5

1.55

1.6

1.65

1.7

1.75

1.8

1.85

1.5

1.55

1.6

1.65

1.7

1.75

1.8

1.85

1%

2%

3%

4%

5%
Ultrasonic Wave Compressional Velocity
LaRC-SI

Sample Set 5a

Legend
- Median
- - - - - 25%, 75%
[Box] 5%, 95%
### Mean±SD

Compressional Velocity (m/s)

Molecular Weight Offset

2558±5
2566±7
2562±3
2593±6
2535±4
### Measured Density of Molded Samples Using Archimede's Principle

<table>
<thead>
<tr>
<th>Molecular Weight</th>
<th>Offset</th>
<th>Density (x10^3 Kg/m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1.3648±0.0002</td>
<td>1.3648±0.0002</td>
<td>1.3648±0.0002</td>
</tr>
<tr>
<td>1.3648±0.0002</td>
<td>1.3648±0.0002</td>
<td>1.3648±0.0002</td>
</tr>
<tr>
<td>1.3648±0.0002</td>
<td>1.3648±0.0002</td>
<td>1.3648±0.0002</td>
</tr>
<tr>
<td>1.3648±0.0002</td>
<td>1.3648±0.0002</td>
<td>1.3648±0.0002</td>
</tr>
</tbody>
</table>
Elastic Properties

- Unrelaxed moduli, linear

- Elastic constants, Young's modulus, shear modulus, Poisson's ratio, bulk modulus
## Wave Velocities as a Function of Molecular Weight Offset

<table>
<thead>
<tr>
<th>Molecular Weight Offset</th>
<th>Shear Velocity (m/s)</th>
<th>Compressional Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
<td>90°</td>
</tr>
<tr>
<td>1%</td>
<td>1.0927±.001</td>
<td>1.0935±.001</td>
</tr>
<tr>
<td>2%</td>
<td>1.0984±.001</td>
<td>1.0986±.001</td>
</tr>
<tr>
<td>3%</td>
<td>1.0928±.0007</td>
<td>1.0940±.001</td>
</tr>
<tr>
<td>4%</td>
<td>1.0943±.002</td>
<td>1.0949±.002</td>
</tr>
<tr>
<td>5%</td>
<td>1.0942±.002</td>
<td>1.0948±.002</td>
</tr>
<tr>
<td>Molecular Weight Offset</td>
<td>Shear Modulus (GPa)</td>
<td>Compressional Modulus (GPa)</td>
</tr>
<tr>
<td>-------------------------</td>
<td>---------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td></td>
<td>$0^\circ$</td>
<td>$90^\circ$</td>
</tr>
<tr>
<td>1%</td>
<td>1.6266±0.004</td>
<td>1.6290±0.004</td>
</tr>
<tr>
<td>2%</td>
<td>1.6451±0.003</td>
<td>1.6456±0.003</td>
</tr>
<tr>
<td>3%</td>
<td>1.6277±0.002</td>
<td>1.6311±0.004</td>
</tr>
<tr>
<td>4%</td>
<td>1.6301±0.007</td>
<td>1.6319±0.006</td>
</tr>
<tr>
<td>5%</td>
<td>1.6341±0.006</td>
<td>1.6358±0.006</td>
</tr>
</tbody>
</table>
# Moduli Derived from Ultrasonics Results: Engineering Moduli (Isentropic)

<table>
<thead>
<tr>
<th>Molecular Weight Offset</th>
<th>Shear Modulus (GPa)</th>
<th>Young’s Modulus (GPa)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>1.6278±.004</td>
<td>4.5199±.046</td>
<td>0.3860±.007</td>
</tr>
<tr>
<td>2%</td>
<td>1.6453±.003</td>
<td>4.5667±.026</td>
<td>0.3878±.003</td>
</tr>
<tr>
<td>3%</td>
<td>1.6294±.004</td>
<td>4.5265±.013</td>
<td>0.3887±.001</td>
</tr>
<tr>
<td>4%</td>
<td>1.6320±.007</td>
<td>4.5324±.062</td>
<td>0.3886±.004</td>
</tr>
<tr>
<td>5%</td>
<td>1.6350±.006</td>
<td>4.5409±.041</td>
<td>0.3887±.004</td>
</tr>
<tr>
<td>Molecular Weight Offset</td>
<td>1%</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Isentropic Bulk Modulus (GPa)</td>
<td>6.7504±0.04</td>
<td>6.7836±0.03</td>
<td>6.7751±0.02</td>
</tr>
</tbody>
</table>
Conclusions

- Molding of LaRC Samples affected the densities of the samples

- Samples have inclusions and show evidence of residual stresses under polarized light. We think that this is responsible for some of the data scatter.

- The 0° and 90° shear measurements show that the assumption of isotropy is a valid one in this case, even with the residual effects left from the moulding process.

- It is possible to calculate the significant engineering moduli from ultrasonic measurements.
Future Planned Activities

- Measurement of the nonlinear moduli

- Measurement of coefficients of linear expansion

- Measurements of effects on moduli (linear and nonlinear) of raising LARC to glass transition temperature and beyond to
PREDICTING BULK POLYMER PROPERTIES

FROM MOLECULAR STRUCTURE

Elizabeth Collantes, Tamara Gahimer, and William Welsh
University of Missouri

Michael Grayson
McDonnell Douglas Aerospace-St. Louis
GOALS & OBJECTIVES

- DEVELOP AND APPLY METHODS IN COMPUTATIONAL CHEMISTRY FOR FAST, RELIABLE, PREDICTION OF POLYMER PROPERTIES

- RELATE BULK MACROSCOPIC POLYMER PROPERTIES TO MICROSCOPIC MOLECULAR STRUCTURE AND PROPERTIES

- DEVELOP STRUCTURE-PROPERTY RELATIONSHIPS
COMPUTATIONAL APPROACHES

- QUANTITATIVE STRUCTURE-PROPERTY RELATIONSHIPS (QSPR)
  - Group-Additivity Techniques (van Krevelen, Dow)
  - Connectivity Indices (Bicerano’s Synthia)

- MULTIVARIATE REGRESSION
  - Partial Least Squares (PLS)

- ARTIFICIAL NEURAL NETWORKS (ANNs)

- ATOMISTIC MOLECULAR MODELING
  - Cerius$^2$ Mechanical Properties Module
DESCRIPTION OF METHODS

QSPR Approaches
QSPR Approaches

The van Krevelen Method

*D. W. van Krevelen, Properties of Polymers: Their Estimation and Correlation with Chemical Structure (Elsevier, 1976)*

- assumes that the physiochemical properties of a polymer can be obtained by adding contributions from the constituent chemical groups

- this approach is commonly known as Group Additivity (GA)

- based on empirical and semi-empirical fitting to expt'l data

- relies on large database containing group contributions, typically one for each property of interest (e.g., $T_g$, $\alpha_T$)

- property values apply to bulk amorphous and semi-crystalline homopolymers, statistical polymers, and for polymer solutions

**Advantages**

→ fast
→ easy to use
→ applicable to many properties
→ usually reliable

**Disadvantages**

→ depends on chemical-fragment library
→ theoretically less rigorous than atomistic methods
→ do not account for special interactions (e.g., solvent)
→ do not provide insight into mechanism
<table>
<thead>
<tr>
<th>Table 9-12. QSPR Groups (Page 1 of 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>-CH₂-</strong></td>
</tr>
<tr>
<td>1. methylene</td>
</tr>
<tr>
<td>[Diagram]</td>
</tr>
<tr>
<td><strong>5. cyclopropylmethylene</strong></td>
</tr>
<tr>
<td>[Diagram]</td>
</tr>
<tr>
<td><strong>9. hydroxymethylene</strong></td>
</tr>
<tr>
<td>[Diagram]</td>
</tr>
<tr>
<td><strong>13. cyanomethyl</strong></td>
</tr>
<tr>
<td>[Diagram]</td>
</tr>
<tr>
<td><strong>17. phenylmethyl</strong></td>
</tr>
<tr>
<td>[Diagram]</td>
</tr>
<tr>
<td><strong>21. dichloromethyl</strong></td>
</tr>
<tr>
<td>[Diagram]</td>
</tr>
<tr>
<td>No.</td>
</tr>
<tr>
<td>------</td>
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<tr>
<td>25.</td>
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<td>26.</td>
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<td>27.</td>
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<td>46.</td>
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<td>47.</td>
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<td>48.</td>
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Table 9-12. QSPR Groups (Page 2 of 3)
Table 9-12. QSPR Groups (Page 3 of 3)

<p>| | | | |</p>
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<th></th>
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<tbody>
<tr>
<td>O</td>
<td>N-N</td>
<td>N-N</td>
<td>C-C-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>49. oxadiazole</td>
<td>50. thiodiazole</td>
<td>51. 25thiazole</td>
<td>52. phthalimide</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>N-N</td>
<td>C-C-</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>53. benzoimidazole</td>
<td>54. benzodimidazole</td>
<td>55. benzodithiazole</td>
<td>56. benzodioxazole</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>57. parabiphenylene</td>
<td>58. bisphenylmethylene</td>
<td>59. bisphenylA</td>
<td>60. bisphenylether</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>61. bisphenylS</td>
<td>62. bisphenylcarbonyl</td>
<td>63. bisphenylsulphone</td>
<td>64. bisphenylmethphenmeth</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65. bisphendiphenmeth</td>
<td>66. ptermethbisphenolA</td>
<td>67. 27naphthalene</td>
<td>68. isobutylmethylene</td>
</tr>
</tbody>
</table>

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van Krevelen Methodology

The polymer properties that can be calculated with the van Krevelen methodology are:

Thermophysical Properties

- glass transition temperature
- crystalline melt transition temperature
- attainable degree of crystallinity
- maximum linear growth rate of sperulitic crystallites
- density of glassy, rubbery and crystalline phases
- volume coefficients of thermal expansion
- volume change on melting
- molar heat capacity at constant pressure
- molar heat capacity at constant volume
- molar entropy of fusion
- molar latent heat of fusion
- cohesive energy
- solubility parameter
- surface tension

Mechanical Properties

- bulk modulus
- Poisson's ratio
- longitudinal velocity of sound
- shear modulus of an amorphous or semicrystalline polymer
- tensile modulus of an amorphous or semicrystalline polymer
Ultimate Mechanical Properties
- tensile yield strength
- compressive strength
- flexural strength
- indentation hardness

Transport Properties
Permeation of a Gas
- specific permachor
- permeability of a gas

Viscoelastic Properties of a Polymer Melt
- activation energy of viscous flow
- Newtonian viscosity
- characteristic deformation time
- non-Newtonian viscosity

Dilute Solution Properties in a theta Solvent
- Mark–Houwink prefactor
- intrinsic viscosity
- radius of gyration
- critical molecular mass for entanglement

Dilute Solution Properties in a Good Solvent
- Mark–Houwink prefactor and exponent
- excluded volume expansion factor
- intrinsic viscosity
- radius of gyration

Concentrated Solution Property in a Good Solvent
- Newtonian viscosity

Electrical, Optical, and Magnetic Properties
- dielectric constant
- resistivity
- refractive index
- magnetic susceptibility
Properties Relating to Thermal Stability

- free enthalpy of formation
- temperature at half thermal decomposition
- char residue
- oxygen index

The van Krevelen methodology relies on the calculation of various molar properties of the average repeat unit. These molar properties are denoted here by enclosure in braces \{\}. The molar properties are then used in the calculation of the macroscopic properties of the polymer. The molar properties that are calculated are listed below:

- mass \(M\)
- number of QSPR groups \(N\)
- number of backbone atoms \(Z\)
- van der Waals volume \(V_W\)
- glass transition temperature \(T_g\)
- melt transition temperature \(T_m\)
- volume at 298 K in the amorphous phase \(V_a\)
- heat capacity of the solid \(C_{p,s}\)
- heat capacity of the liquid \(C_{p,l}\)
- entropy of melting \(\Delta S_m\)
- cohesive energy \(E_{coh}\)
- interaction \(F\)
- parachor \(P_p\)
- permachor \(\Pi\)
- elastic wave velocity \(U\)
- intrinsic viscosity \(\eta\)
- viscosity–temperature gradient \(H_h\)
- polarization \(P_{LL}\)
- optical refraction \(R_{GD}\)
- magnetic susceptibility \(\chi\)
- enthalpy of formation \(\Delta G_a\)
- entropy of formation \(\Delta G_b\)
- half thermal decomposition temperature \(Y_{d,1/2}\)
- char forming tendency \(C_f\)
QSPR Approaches

The Dow Method

- adopts group-additivity (GA) concept, but uses only six group contributions of the repeat unit to predict polymer properties: (1) molecular weight; (2) length; (3) vDW volume; (4) cohesive energy; (5) rotational df of the backbone; and (6) $T_g$

- focuses on mechanical properties

- limited to amorphous (not semi-crystalline) polymers

Advantages
- same advantages as van Krevelen: fast, reliable
- less dependent on large database of group contributions
- better fitted to high-performance engineering polymers
- conceptually more rigorous than van Krevelen

Disadvantages
- same disadvantages as van Krevelen
- restricted to amorphous polymers
- depends on library of group contributions, although smaller
Properties Calculable

Dow Methodology

With the Dow methodology implemented within the QSPR module it is possible to predict 17 different properties of amorphous thermoplastic polymers. These are:

- Molar volume per repeat unit
- Density
- Thermal expansion coefficient
- Cohesive energy
- Solubility parameter
- Surface tension
- Dielectric constant
- Average molecular cross-sectional area
- Glass transition temperature
- Poisson’s ratio
- Tensile modulus
- Tensile yield strength
- Brittle strength
- Crazing strength
- Entanglement molecular weight
- Distance between entanglements
- Plateau modulus

In addition, if $T_g > 300$ K, many of these properties may be calculated as a function of temperature.

The group parameters required to predict these properties are:

- Molecular weight
- Length per repeat unit
- van der Waals volume
- Cohesive energy
- Molar glass transition temperature
- Number of backbone rotatable units
QSPR Approaches

Bicerano’s Synthia Method
J. Bicerano, Prediction of Polymer Properties (Marcel Dekker, 1993)

- circumvents reliance on group contributions by relating polymer properties to topological information about polymers using connectivity indices derived from graph theory

- useful for any polymer comprised of the following elements: C, H, N, O, Si, S, F, Cl, Br

- applicable to bulk amorphous homopolymers and statistical copolymers

Advantages
→ independent of large group-contribution library
→ thermodynamic, mechanical, and transport properties

Disadvantages
→ restricted to nine atom-types
→ restricted to amorphous polymers
→ does no account for special interactions
Table 11-1. Properties Calculable By the Synthia Module

<table>
<thead>
<tr>
<th>Thermophysical Properties</th>
<th>Electrical, Optical and Magnetic Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass transition temperature</td>
<td>Refractive index</td>
</tr>
<tr>
<td>Temperature of half decomposition</td>
<td>Molar refraction</td>
</tr>
<tr>
<td>Coefficient of volumetric thermal expansion</td>
<td>Dielectric constant</td>
</tr>
<tr>
<td>Molar volume</td>
<td>Volume resistivity</td>
</tr>
<tr>
<td>Density</td>
<td>Diamagnetic susceptibility</td>
</tr>
<tr>
<td>Molar heat capacity at constant pressure</td>
<td></td>
</tr>
<tr>
<td>Cohesive energy</td>
<td>Chain Stiffness and Entanglement Properties</td>
</tr>
<tr>
<td>Solubility parameter</td>
<td>Steric hindrance parameter</td>
</tr>
<tr>
<td>Surface tension</td>
<td>Characteristic ratio</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>Molar stiffness function</td>
</tr>
<tr>
<td>Mechanical Properties</td>
<td>Entanglement molecular weight</td>
</tr>
<tr>
<td>Bulk modulus</td>
<td>Critical molecular weight</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>Entanglement length</td>
</tr>
<tr>
<td>Young's modulus</td>
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</tr>
<tr>
<td>Poisson's ratio</td>
<td>Transport Properties</td>
</tr>
<tr>
<td>Shear yield stress</td>
<td>Activation energy for viscous flow</td>
</tr>
<tr>
<td>Brittle fracture stress</td>
<td>Permeability of gases</td>
</tr>
</tbody>
</table>

169
DESCRIPTION OF METHODS

Multivariate PLS Approach
Multivariate PLS Approach
Attempts to eliminate any dependence on group contributions or connectivity indices

• relate bulk polymer properties to specific molecular descriptors associated with the repeat unit

• focused on two polymer properties: $T_g$ and Tensile Modulus

• selected seven easily-obtainable molecular descriptors: (1) molecular weight; (2) length; (3) number of atoms; (4) number of non-H atoms; (5) vDW volume; (6) rotational df, and (7) number of backbone atoms

• develops linear regression equation to map bulk polymer property onto calculable descriptors thereby allowing prediction of polymer property solely from knowledge of descriptors

\[
\text{property value} = a_1 (PC_1) + a_2 (PC_2) + a_3 (PC_3) + ...
\]

• applicable to any series of polymers for which experimental data is available

---

**Advantages**
\rightarrow totally independent of any database library
\rightarrow generally applicable to any property and any polymer
\rightarrow from Loadings, evaluates contribution by each descriptor to property of interest

**Disadvantages**
\rightarrow assumes linear relationship between property and descriptors
\rightarrow need expt’l data on related polymers to develop regression equation

171
PLS: GRAPHICAL REPRESENTATION

Polymer property space

Chemical descriptor space

Inner relation
Determining the number of significant components

- cross-validation
DESCRIPTION OF METHODS

Artificial Neural Networks
Artificial Neural Networks (ANN)
paradigm based on architecture of biological network of
neurons in human brain

- ANNs learn by repetition (like a child) to generate a desired
  response (output) based on knowledge of specific stimuli
  (inputs)

- learns to map bulk polymer property (output) onto calculable
  molecular descriptors (inputs), thereby allowing prediction of
  polymer properties solely from knowledge of these descriptors

- applicable to any series of polymers for which experimental
data is available

- focused on same two polymer properties as outputs: $T_g$ and
  Tensile Modulus

- selected identical seven molecular descriptors as inputs: (1)
molecular weight; (2) length; (3) number of atoms; (4) number
of non-H atoms; (5) vdW volume; (6) rotational df, and (7)
number of backbone atoms

Advantages
→ totally independent of any fragment database
→ generally applicable to any property and to any polymer
→ inherently nonlinear and tolerant of noisy data

Disadvantages
→ requires expt'l data on related polymers to train the network
prior to making predictions
List of Inputs (per repeat unit)

1. molecular weight
2. end-to-end length
3. number of atoms
4. number of non-H atoms
5. vdW volume
6. rotational degrees of freedom
7. number of backbone atoms
SUMMARY OF RESULTS
Figure 1. Repeat units of polymers included in this QSPR study

PMR-15

LARC-CPI

LARC-CPI-2

LARC-TPI

LARC-I-TPI

Kapton

PEEK

LARC-SI
### Table I
Abbreviated List of Calculated Properties of Polymides and PEEK

<table>
<thead>
<tr>
<th>PROPERTY&lt;sup&gt;a&lt;/sup&gt;</th>
<th>UNIT</th>
<th>LARC-</th>
<th>LARC-</th>
<th>LARC-</th>
<th>LARC-</th>
<th>PMR-</th>
<th>PETI-2</th>
<th>PETI-4</th>
<th>KAPTON</th>
<th>PEEK</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CPI</td>
<td>CPI2</td>
<td>TPI</td>
<td>ITPI</td>
<td>SI</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass Transition Temperature, T&lt;sub&gt;G&lt;/sub&gt;</td>
<td>K</td>
<td>486</td>
<td>488</td>
<td>532</td>
<td>534</td>
<td>520</td>
<td>518</td>
<td>516</td>
<td>522</td>
<td>628</td>
</tr>
<tr>
<td>Melt Transition Temperature&lt;sup&gt;b&lt;/sup&gt;, T&lt;sub&gt;m&lt;/sub&gt;</td>
<td>K</td>
<td>707</td>
<td>726</td>
<td>744</td>
<td>746</td>
<td>755</td>
<td>733</td>
<td>755</td>
<td>754</td>
<td>850</td>
</tr>
<tr>
<td>Coef. of Thermal Expansion&lt;sup&gt;c&lt;/sup&gt;, α</td>
<td>ppm/K</td>
<td>206</td>
<td>204</td>
<td>192</td>
<td>187</td>
<td>183</td>
<td>186</td>
<td>190</td>
<td>177</td>
<td>147</td>
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<tr>
<td>Density, ρ, at 298 K</td>
<td>g/cm³</td>
<td>1.36</td>
<td>1.36</td>
<td>1.43</td>
<td>1.43</td>
<td>1.43</td>
<td>1.40</td>
<td>1.44</td>
<td>1.43</td>
<td>1.38</td>
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<tr>
<td>Solubility Parameter, δ</td>
<td>MPa&lt;sup&gt;1/2&lt;/sup&gt;</td>
<td>25.6</td>
<td>25.3</td>
<td>27.2</td>
<td>27.2</td>
<td>26.5</td>
<td>26.6</td>
<td>26.6</td>
<td>25.3</td>
<td>22.8</td>
</tr>
<tr>
<td>Cohesive Energy, E&lt;sub&gt;coh&lt;/sub&gt;</td>
<td>kJ/mole</td>
<td>378.5</td>
<td>364.5</td>
<td>258.6</td>
<td>258.6</td>
<td>457.8</td>
<td>246.2</td>
<td>230.6</td>
<td>227.2</td>
<td>177.2</td>
</tr>
<tr>
<td>Attainable Degree of Crystallinity&lt;sup&gt;d&lt;/sup&gt;, X&lt;sub&gt;c&lt;/sub&gt;</td>
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<td>0.46</td>
<td>0.37</td>
<td>0.37</td>
<td>0.42</td>
<td>0.39</td>
<td>0.43</td>
<td>0.42</td>
<td>0.32</td>
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<tr>
<td>Free Enthalpy of Formation&lt;sup&gt;d&lt;/sup&gt;, ΔG&lt;sub&gt;f&lt;/sub&gt;</td>
<td>kJ/mole</td>
<td>-1046</td>
<td>-1046</td>
<td>-686.0</td>
<td>-686.0</td>
<td>-1224</td>
<td>-600.0</td>
<td>-686.0</td>
<td>-538.0</td>
<td>-565.0</td>
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### THERMOPHYSICAL PROPERTIES

### MECHANICAL PROPERTIES at 298 K

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<thead>
<tr>
<th>Property</th>
<th>UNIT</th>
<th>LARC-CPI</th>
<th>LARC-CPI2</th>
<th>LARC-TPI</th>
<th>LARC-ITPI</th>
<th>LARC-SI</th>
<th>PMR-15</th>
<th>PETI-2</th>
<th>PETI-4</th>
<th>KAPTON</th>
<th>PEEK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Modulus, E</td>
<td>GPa</td>
<td>3.63</td>
<td>3.41</td>
<td>4.24</td>
<td>4.13</td>
<td>4.46</td>
<td>4.03</td>
<td>4.02</td>
<td>3.90</td>
<td>3.93</td>
<td>2.42</td>
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<tr>
<td>Tensile Yield Strength, σ&lt;sub&gt;y&lt;/sub&gt;</td>
<td>MPa</td>
<td>90.8</td>
<td>85.3</td>
<td>105.9</td>
<td>103.2</td>
<td>111.5</td>
<td>100.8</td>
<td>100.4</td>
<td>97.4</td>
<td>98.3</td>
<td>60.4</td>
</tr>
<tr>
<td>Poisson’s Ratio, μ</td>
<td>MPa</td>
<td>0.406</td>
<td>0.410</td>
<td>0.408</td>
<td>0.411</td>
<td>0.397</td>
<td>0.407</td>
<td>0.406</td>
<td>0.410</td>
<td>0.407</td>
<td>0.414</td>
</tr>
<tr>
<td>Ultimate Compressive Strength&lt;sup&gt;b&lt;/sup&gt;, σ&lt;sub&gt;comp&lt;/sub&gt;</td>
<td>MPa</td>
<td>235.7</td>
<td>237.9</td>
<td>283.1</td>
<td>284.8</td>
<td>270.2</td>
<td>268.4</td>
<td>266.5</td>
<td>272.3</td>
<td>394.0</td>
<td>168.9</td>
</tr>
<tr>
<td>Brittle Strength, σ&lt;sub&gt;b&lt;/sub&gt;</td>
<td>MPa</td>
<td>124.4</td>
<td>134.3</td>
<td>128.7</td>
<td>135.1</td>
<td>104.7</td>
<td>126.8</td>
<td>124.2</td>
<td>134.4</td>
<td>128.1</td>
<td>142</td>
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</tbody>
</table>

---

<sup>a</sup> Based on DOW QSRR method, unless otherwise noted.

<sup>b</sup> Based on van Krevelen QSRR method.

<sup>c</sup> Based on Synthia method.
<table>
<thead>
<tr>
<th>PROPERTY(\alpha)</th>
<th>UNIT</th>
<th>LARC-CP</th>
<th>LARC-CP2</th>
<th>LARC-TP</th>
<th>LARC-ITP</th>
<th>LARC-SI</th>
<th>PMR-15</th>
<th>PETI-2</th>
<th>PETI-4</th>
<th>KAPTON</th>
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<td><strong>THERMOPHYSICAL PROPERTIES</strong></td>
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<tr>
<td>Glass Transition Temperature, (T_g)</td>
<td>(K)</td>
<td>486</td>
<td>488</td>
<td>532</td>
<td>534</td>
<td>520</td>
<td>518</td>
<td>516</td>
<td>522</td>
<td>628</td>
<td>411</td>
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<tr>
<td>Melt Transition Temperature(b), (T_m)</td>
<td>(K)</td>
<td>707</td>
<td>726</td>
<td>744</td>
<td>746</td>
<td>755</td>
<td>733</td>
<td>755</td>
<td>754</td>
<td>850</td>
<td>627</td>
</tr>
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<td>Coef. of Thermal Expansion(\alpha)</td>
<td>ppm/K</td>
<td>206</td>
<td>204</td>
<td>192</td>
<td>187</td>
<td>183</td>
<td>186</td>
<td>190</td>
<td>177</td>
<td>147</td>
<td>227</td>
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<tr>
<td>Molar Volume at 298 K</td>
<td>cm(^3)/mo</td>
<td>579.2</td>
<td>569.2</td>
<td>348.4</td>
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<td>651.0</td>
<td>347</td>
<td>329.4</td>
<td>321.7</td>
<td>277.5</td>
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<tr>
<td>Density, (\rho), at 298 K</td>
<td>g/cm(^3)</td>
<td>1.36</td>
<td>1.36</td>
<td>1.43</td>
<td>1.43</td>
<td>1.43</td>
<td>1.40</td>
<td>1.44</td>
<td>1.43</td>
<td>1.38</td>
<td>1.25</td>
</tr>
<tr>
<td>Solubility Parameter, (\delta)</td>
<td>MPa(^1/\alpha)</td>
<td>25.6</td>
<td>25.3</td>
<td>27.2</td>
<td>27.2</td>
<td>26.5</td>
<td>26.6</td>
<td>26.5</td>
<td>26.6</td>
<td>25.3</td>
<td>22.8</td>
</tr>
<tr>
<td>Cohesive Energy, (E_{coh})</td>
<td>kJ/mol</td>
<td>378.5</td>
<td>364.5</td>
<td>258.6</td>
<td>258.6</td>
<td>457.8</td>
<td>246.2</td>
<td>230.6</td>
<td>227.2</td>
<td>177.2</td>
<td></td>
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<tr>
<td>Molar Heat Capacity(b): at constant (P),</td>
<td>J/mol-K</td>
<td>766.0</td>
<td>760.5</td>
<td>473.7</td>
<td>473.7</td>
<td>905.6</td>
<td>476.1</td>
<td>461.2</td>
<td>444.4</td>
<td>365.0</td>
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<tr>
<td>(\gamma) at constant (V),</td>
<td>J/mol-K</td>
<td>674.9</td>
<td>661.9</td>
<td>419.6</td>
<td>419.6</td>
<td>781.7</td>
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<td>382.7</td>
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<tr>
<td>(\gamma) at (T_g)</td>
<td>dyn/c</td>
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<td>55.72</td>
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<td>61.50</td>
<td>59.31</td>
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<td>55.62</td>
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<tr>
<td>Thermal Conductivity(c): at 298 K</td>
<td>J/Kms</td>
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<td>0.20</td>
<td>0.20</td>
<td>0.21</td>
<td>0.20</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
<td>0.20</td>
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<tr>
<td>(\gamma) at (T_g)</td>
<td>vol frac</td>
<td>0.43</td>
<td>0.46</td>
<td>0.37</td>
<td>0.37</td>
<td>0.42</td>
<td>0.39</td>
<td>0.43</td>
<td>0.42</td>
<td>0.32</td>
<td>0.49</td>
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<tr>
<td>Av. Molecular Cross Sectional Area</td>
<td>(A^2)</td>
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<td>18.71</td>
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<td>18.70</td>
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<td>19.90</td>
<td>20.30</td>
<td>18.78</td>
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</tbody>
</table>

**PROPERTY RELATING TO THERM. STABILITY**

<p>| Free Enthalpy of Formation(b), (\Delta G_f)       | kJ/mol | -1046   | -1046    | -686.0  | -686.0   | -1224  | -600.0 | -686.0 | -538.0 | -565.0 | -360.0 |</p>
<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>UNIT</th>
<th>LARC-CPI</th>
<th>LARC-CPI2</th>
<th>LARC-TPI</th>
<th>LARC-ITPI</th>
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<th>PETI-4</th>
<th>KAPTON</th>
<th>PEEK</th>
</tr>
</thead>
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<tr>
<td><em>MECHANICAL PROPERTIES at 298 K</em></td>
<td></td>
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<td>Tensile Modulus, E</td>
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<td>3.41</td>
<td>4.24</td>
<td>4.13</td>
<td>4.46</td>
<td>4.03</td>
<td>4.02</td>
<td>3.90</td>
<td>3.93</td>
<td>2.42</td>
</tr>
<tr>
<td>Tensile Yield Strength, σ_y</td>
<td>MPa</td>
<td>90.8</td>
<td>85.3</td>
<td>105.9</td>
<td>103.2</td>
<td>111.5</td>
<td>100.8</td>
<td>100.4</td>
<td>97.4</td>
<td>98.3</td>
<td>60.4</td>
</tr>
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<td>1.368</td>
<td>1.343</td>
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<tr>
<td>Poisson's Ratio, μ</td>
<td></td>
<td>0.406</td>
<td>0.410</td>
<td>0.408</td>
<td>0.411</td>
<td>0.397</td>
<td>0.407</td>
<td>0.406</td>
<td>0.410</td>
<td>0.407</td>
<td>0.414</td>
</tr>
<tr>
<td>Ultimate Compressive Strength,</td>
<td>MPa</td>
<td>235.7</td>
<td>237.9</td>
<td>283.1</td>
<td>284.8</td>
<td>270.2</td>
<td>268.4</td>
<td>266.5</td>
<td>272.3</td>
<td>394.0</td>
<td>168.9</td>
</tr>
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<td>Brittle Strength, σ_b</td>
<td>MPa</td>
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<td>134.3</td>
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<td>124.2</td>
<td>134.4</td>
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<td>142</td>
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<td>123.3</td>
<td>128.3</td>
<td>128.5</td>
<td>125.9</td>
<td>125.4</td>
<td>125.7</td>
<td>126.0</td>
<td>136.7</td>
<td>116.8</td>
</tr>
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<td>Shear Yield Stress, σ_{II}</td>
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<td>17.0</td>
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<td>1.53</td>
<td>2.17</td>
<td>2.05</td>
<td>2.58</td>
<td>2.89</td>
<td>1.63</td>
</tr>
</tbody>
</table>

| ELECTRICAL, OPTICAL, AND MAGNETIC |
|-----------------------------------|------|----------|-----------|----------|-----------|---------|--------|--------|--------|--------|------|
| Refractive Index, n               |      | 1.643    | 1.644     | 1.657    | 1.657     | 1.664   | 1.66   | 1.661  | 1.663  | 1.663  | 1.619 |
| Molar Refraction (Lorentz and     |      | 215.7    | 213.1     | 133.3    | 133.3     | 251.4   | 133.2  | 128.1  | 125.8  | 103.07 | 82.08 |
| Dielectric Constant, ε            |      | 3.42     | 3.36      | 3.65     | 3.65      | 3.46    | 3.49   | 3.48   | 3.44   | 3.60   | 3.04 |
| Volume Resistivity (x10^-16)      | ohm-cm| 1.45     | 1.89      | 0.49     | 0.49      | 1.20    | 1.03   | 1.12   | 1.29   | 0.641  | 8.29 |
| Diamagnetic Susceptibility (x10^6) | cm^3/mo| 423.8    | 422.5     | 254.6    | 254.6     | 497.9   | 258.6  | 251.9  | 245.9  | 196.0  | 169.2 |
### Table II (continued)

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>UNIT</th>
<th>LARC-CH</th>
<th>LARC-CRI</th>
<th>LARC-TPI</th>
<th>LARC-ITPI</th>
<th>LARC-SI</th>
<th>PMR-1B</th>
<th>PETI-2</th>
<th>PETI-4</th>
<th>KAPTON</th>
<th>PEEK</th>
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<tr>
<td><strong>MECHANICAL PROPERTIES AT INCEPTION OF RUBBERY PLATEAU</strong></td>
<td></td>
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<tr>
<td>Temperature</td>
<td>K</td>
<td>512</td>
<td>517</td>
<td>549</td>
<td>564</td>
<td>576</td>
<td>566</td>
<td>555</td>
<td>594</td>
<td>717</td>
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<td>Molar Volume</td>
<td>cm³/mo</td>
<td>626.41</td>
<td>618.41</td>
<td>382.06</td>
<td>382.52</td>
<td>715.92</td>
<td>381.10</td>
<td>365.57</td>
<td>357.41</td>
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<td>Density</td>
<td>g/cm³</td>
<td>1.256</td>
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<td>1.303</td>
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<td>Bulk Modulus</td>
<td>MPa</td>
<td>2766</td>
<td>2604</td>
<td>3121</td>
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<td>3000</td>
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<td>Tensile Modulus</td>
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<td>6.17</td>
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<td>5.42</td>
<td>6.51</td>
<td>5.58</td>
<td>7.76</td>
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<td>Activation Energy for Viscous Flow</td>
<td>kJ/mol</td>
<td>69.55</td>
<td>68.87</td>
<td>70.96</td>
<td>70.96</td>
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<td>68.81</td>
<td>70.83</td>
<td>69.70</td>
<td>67.14</td>
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<td>Permeability at 298 K : O₂</td>
<td>Dow</td>
<td>23.2</td>
<td>34.1</td>
<td>10.9</td>
<td>10.9</td>
<td>33.5</td>
<td>24.3</td>
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<td>157.2</td>
<td>158.7</td>
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<td>305.0</td>
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* Based on DOW QSRR method, unless otherwise noted.

* Based on van Krevelen QSRR method.

* Based on Synthia method.
Table III. List of Experimental Properties of Polyimides and PEEK

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>UNIT</th>
<th>LARC-CPI</th>
<th>LARC-CPI2</th>
<th>LARC-TPI</th>
<th>LARC-ITPI</th>
<th>LARC-SI</th>
<th>PMR-15</th>
<th>PETI-2</th>
<th>PETI-4</th>
<th>KAPTON</th>
<th>PEEK</th>
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<tbody>
<tr>
<td>Glass Transition Temperature, ( T_g )</td>
<td>K</td>
<td>495(^{14})</td>
<td>490(^{14})</td>
<td>513(^{2})</td>
<td>532(^{14,11})</td>
<td>600(^{2})</td>
<td>658(^{1})</td>
<td>418(^{1})</td>
<td>416(^{2})</td>
<td>417(^{2})</td>
<td></td>
</tr>
<tr>
<td>Melt Transition Temperature, ( T_m )</td>
<td>K</td>
<td>623(^{1,2})</td>
<td>548(^{1})</td>
<td>578(^{2})</td>
<td>613(^{9})</td>
<td>770(^{1})</td>
<td>597(^{1})</td>
<td>616(^{2,12})</td>
<td>613(^{7})</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Coef. of Thermal Expansion, \( \alpha \) | \( \text{in/in}^\circ\text{F} \) | 1.55\(^{2}\) | 1.37\(^{2}\) | 28(10^{-6})\(^{8}\) | 1.58\(^{2}\) | 1.32\(^{2}\) | 1.42\(^{1}\) | 1.20\(^{4}\) | 1.26\(^{7}\) | 1.31\(^{8}\) | 22(10^{-4})\(^{7}\) 
| Density, \( \rho \)                    | g/cm\(^3\) |          |           |          |           |         | 3.2\(^{5}\) | 2.10\(^{3}\) | 3.71\(^{1}\) |          | 3.81\(^{8}\) |
| Tensile Modulus, \( E \)               | GPa  | 4.27\(^{10}\) | 3.5\(^{9}\) | 3.7\(^{11}\) | 3.71\(^{10,11}\) | 3.2\(^{9}\) | 3.2\(^{9}\) | 2.96\(^{5}\) | 3.81\(^{9}\) | 1.34\(^{18}\) |
| Tensile Yield Strength, \( \sigma \)    | MPa  | 3.10\(^{14}\) | 103.4\(^{2}\) | 96.6\(^{2}\) | 3.30\(^{4}\) | 3.29\(^{4}\) | 3.5\(^{1}\) | 3.22\(^{6}\) | 3.3\(^{7}\) | 3.3\(^{7}\) |

References
7. Data Sheet for STABAR K200.
8. Data Sheet for Fibrelite966C.
QSPR-calculated Thermophysical Properties for Various Polyimides
QSPR-calculated Mechanical Properties for Various Polyimides
QSPR-calculated Mechanical Properties

Values for the respective Mechanical Property, in MPa

Tensile Yield Strength 189 Ultimate Compr. Strength

Materials:
- TPI, ITPI
- PETI-4, SI
- PMR-15, PETI-2
- CPI, CPI-2
- PEEK
- PMR-2, PETI-2
- TPI, KARTON
- CPI, PETI-2
- SI
EXPERIMENTAL POLYMER PROPERTIES

+ 

NEURAL NETS    QSPR METHODS    REGRESSION METHODS    ATOMISTIC METHODS

↓ 

ESTABLISH STRUCTURE-PROPERTY RELATIONSHIPS 
RELATE MICROSCOPIC TO MACROSCOPIC PROPERTIES 
PREDICT BULK PROPERTIES FROM MOLECULAR DESCRIPTORS 
CORRELATE WITH EXPERIMENTAL RESULTS
QSPR-calculated Poisson's Ratio vs. Temperature

Temperature, K

0.36 0.38 0.40 0.42 0.44 0.46 0.48

PEEK PMR-15 PETI-2 CPI TPI SI KAPTON
QSPR-calculated Tensile Modulus vs. Temperature

Temperature, K

Tensile Modulus, GPa

100 200 300 400 500 600

1 2 3 4 5 6 7

SI TPI PMR PETI-2 CPI KAPTON PEEK

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### ANN and PLS Calculated $T_g$ vs. Experimental Values

<table>
<thead>
<tr>
<th></th>
<th>Expt'l</th>
<th>Calculated/Predicted $T_g$, K</th>
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</thead>
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<tr>
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<td>$T_g$, K</td>
<td>ANN</td>
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<tr>
<td>CPI</td>
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<td>506</td>
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<td>TPI</td>
<td>523</td>
<td>546</td>
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<td>Kapton</td>
<td>658</td>
<td>634</td>
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<td>SI</td>
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### ANNs and PLS Calculated Tensile Modulus (E) vs. Experimental Values

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<th>Calculated/Predicted E, GPa</th>
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<td>-0.12</td>
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<tr>
<td>TPI</td>
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<td>Kapton</td>
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<td>3.09</td>
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<td></td>
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<td>-0.36</td>
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<tr>
<td>PMR-15</td>
<td>3.9</td>
<td>3.77</td>
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<td>3.65</td>
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<td>CPI-2</td>
<td>3.7</td>
<td>3.7</td>
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<td>3.53</td>
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<td>3.68</td>
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<td>3.49</td>
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<td>PETI-4</td>
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<td>SI</td>
<td>4.13</td>
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CURRENT WORK

- Atomistic Cerius$^2$ calculations of polymer properties: tensile modulus, bulk modulus, speed of sound, Poisson's ratio, density

- EGAMS of neat LaRC-SI resin (with Mike Grayson): experimental and theoretical investigation of thermal degradation

- Dynamic mechanical analysis (DMA) of LaRC-SI resin (with Mike Grayson): measure $T_g$, characterize sub-$T_g$ transitions

- Extend multivariate regression and neural network analysis relating bulk polymer properties to molecular descriptors
SUMMARY AND CONCLUSIONS

QSPR

- All three QSPR methods agree with each other reasonably well in predicting mechanical and thermophysical polymer properties.

- Values of $T_g$ and $E$ predicted by all three QSPR methods agree reasonably well (within 15%) with the corresponding expt’l values.

- Comparing the polyimides, Kapton ranks high in $T_g$ and $T_m$ but low in $\alpha_T$; $T_g$ is slightly higher for para over meta catenation (488K for CPI2 vs. 486K for CPI).

- High $T_g$ and $E$ are inversely related to $\alpha_T$: Kapton vs. PEEK.

- LARC-SI exhibits high values of tensile modulus and tensile yield strength (and low values of Poisson’s ratio) across the $T = 100-600$ K temperature range.

PLS REGRESSION AND NEURAL NETS (ANN)

- For $T_g$, the residual standard deviation (RSD) was 18K for PLS, 20K for ANN, and 37K for QSPR.

- For $E$, the RSD was 0.20 GPA for PLS, 0.12 GPA for ANN, and 0.91 GPA for QSPR-DOW.

- The molecular descriptor with the highest PLS loading was the rotational degrees of freedom for both $T_g$ and $E$.
RESULTS OF ATOMISTIC CERIUS$^2$ CALCULATIONS
cis – PBO
Calculated Tensile Modulus : 354 GPa

Miller planes are highlighted in blue
Table C: University of Akron - C Cerius² Data

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<thead>
<tr>
<th>Structure</th>
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Average 218.195
Multiaxial and Time Dependent Response of Rigid Polymers

W.G. Knauss

California Institute of Technology
Pasadena, California

Supported in part by the Materials Branch at NASA, Langley
The following are the captions for the figures.

1. Title
2. Productions of steel and polymer during last 35 years
3. Long range objectives
4. Constitutive Interest
5. Range of Issues
6. Yield-like behavior
7. Experimental Approaches to Physical Characterization
8. A free volume based constitutive model
9. Comparison of material responses between the free volume model prediction and experimental observation for uniaxial loading and unloading
10. Comparison of material responses between the free volume model prediction and experimental observations for relaxation at different small strain levels
11. Simulation of yield-like behavior from the free volume model
12. Free volume model for large uniaxial strains (polymide)
13. Creep compliance at different stress levels measured by Govaert
14. Master creep compliance curve shifted by Govaert. The master curve is not smooth
15. Comparison of the master creep compliance curve shifted by Govaert and that shifted by H. Lu and W.G. Knauss
16. Zoom of a portion of the master curve "shifted" by Govaert. (The curves do not really fit a shift.)
17. The shift factors measured by Govaert
18. The shift factors measured by H. Lu and W.G. Knauss
19. Displacement measurement resolution of the digital image correlation
20. Shear relaxation modulus measured at 0.2% of shear strain
21. Shear relaxation master curve
22. Young's relaxation modulus measured at 0.2% of axial strain
23. Young's relaxation master curve
24. Shift factors for the Young's and shear modulus master curves
25. Superposed tension or compression increases the shear creep rate under pure torsion well below glass transition (results at 22°C)
26. Superposed tension or compression increases the shear creep rate under pure torsion well below glass transition (results at 50°C)
27. Shear stress also controls the shear creep rate - shear creep compliances at different stress levels
28. Superposed tension or compression increases the shear creep rate under pure torsion well below glass transition (results at 80°C)
29. Under the same torque, a superposed tension increases the torsional creep rate while a superposed compression decreases it in the vicinity of the glass transition (results at 100°C)
30. Under the same torque, a superposed tension increases the torsional creep rate while a superposed compression decreases it in the vicinity of the glass transition (results at 110°C)
31. Under the same shear stress, a superposed tension has a much higher creep rate than a superposed compression, indicating free volume plays a major role in the glassy state
32. Some thoughts on an "activation" rate model incorporating the coupling of volumetric deformation and shear deformation
Annual Tonnage of Steel and Polymer produced during the last 35 years
Establish general polymer constitutive behavior and

Analytically model this behavior

Constitutive behavior must incorporate

Linear and nonlinear viscoelasticity at small and moderate strains (yield-like response)

Nonlinear viscoelasticity at very large strains

under arbitrary load histories, including ageing and "recovery"

Environmental factors:

Temperature dependence, including the range around the glass transition

Solvent influence, including water
Constitutive Interest

Physical properties descriptions involve the whole spectrum of size scales and approaches to analytical formulation

1) Model material behavior for engineering analyses: Application oriented and global view

2) Structure - property relationships: Molecular science orientation and microscopic view
Yield-like behavior is physically different from yielding in metals. In thermoplastic solids it is not necessarily associated with crazing.

"Yield-like behavior" occurs at small strains ($\varepsilon_{\text{uniaxial}} < 5\%$).

"Yield-deformations" are usually recoverable under thermal control.

Yield-like behavior does not involve large scale molecular re-orientation and organization unless it is associated with very localized shear bands.

Molecular orientation occurs in uniaxial deformation at extension ratios exceeding 100%.

Very small changes in volume (>0.1%) have a disproportionate effect on the time-temperature trade-off.

To what degree is yield-like behavior the result of local material instability augmented or controlled by small volume changes?

To what degree is yield-like response controlled or influenced by organized molecular rearrangement?
Range of Issues

1) Time and rate dependence
2) Nonlinear response
3) Thermorheology
4) Glass transition behavior
5) Physical ageing
Experimental Approaches to Physical Characterization

Different stress state histories

There is a lot of data on pressure superposed on uniaxial tension in the literature.

There is no data on biaxial stress states shear-plus-tension or shear-plus-compression.

There is virtually no data on time-dependent bulk behavior.
Constitutive Model (Emri and Knauss, 1981)

Free volume

\[ f = f_0 + A\alpha(t) \cdot dT + \delta\varepsilon_{kk} \]

Time-shift factor, \( \phi \)

\[ \log \phi = \frac{b}{2.303} \left( \frac{1}{f} - \frac{1}{f_0} \right) \]

Internal (reduced) time

\[ d\xi(t) = \frac{dt}{\phi(t)} \quad \text{or} \quad \xi(t) = \int_0^t \frac{du}{\phi[T(u), \theta(u)]} \]

Thermorheologically simple material

\[ S_{ij} = 2 \int_{-\infty}^{t} \mu(\xi - \xi') \frac{\partial e_{ij}(t')}{\partial t'} dt' \]

\[ \sigma_{kk} = 3 \int_{-\infty}^{t} K(\xi - \xi') \frac{\partial \varepsilon_{kk}(t')}{\partial t'} dt' \]

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$T = 26.5 \, ^{\circ}C$
$\varepsilon_0 = 0.01 \, \text{min}^{-1}$
$\varepsilon_0 = 2.8\%$

- A: Linear viscoelastic solid
- B: Experimental data (Instron)
- C: Present analysis
Figure 4.6 Three Term Model Tensile Response

Figure 4.7 Model Results for Variation in Straining Rates on Specimen of 65mm Gauge Length.

M. R. Monaghan
P. Mallon, Univ. of Limerick
Polyimide film
380° C
C/Head 65 mm/min
Displacement Resolution of the Method

A typical field of view is 25 mm (1 inch)

Pixel size: 50 microns/pixel side

The resolution limit for displacements is 3 microns

This translates into resolution of

normal strains of 0.05%

shear strains of 0.05%

circumferential strains of 0.08%
A graph showing the relationship between log(shear creep compliance) and log(time) for different types of loading at 50°C.

- **Tension + Torsion** with $\sigma = 6.3$ MPa, $\tau = 1.8$ MPa, and $\varepsilon_{12} = 1.77\%$.
- **Compression + Torsion** with $\sigma = -6.3$ MPa, $\tau = 1.8$ MPa, and $\varepsilon_{12} = 0.90\%$, $0.87\%$, $0.81\%$.
- **Pure Torsion** with $\sigma = 0$, $\tau = 1.8$ MPa, and strains $1.31\%$, $1.11\%$.

The graph indicates a linear relationship on a log-log scale, with error bars for each data point.
Coupling Between

Volumetric and Shear Response

as Based on an "Activation" Rate Model

\[ \dot{\gamma}^\pm (\tau, \sigma_{ii}) = \pm A_n \exp\{- \frac{1}{RT} [\Delta E^*_n - |v^*_n \tau| - \sigma_{ii} \Omega_n]\} \]

Pool size

\[ \dot{\gamma}^\pm (\tau, \sigma) = \pm A_n \exp\{- \frac{\Delta E^*_n - \sigma_{ii} \Omega_n}{RT}\} \cdot \exp\{\frac{|v^*_n (\tau) \cdot \tau|}{RT}\} \]

\[ \dot{\gamma} = \sum \dot{\gamma}_n = \sum_n 2A_n \exp\{- \frac{\Delta E^*_n - \sigma_{ii} \Omega_n}{RT}\} \cdot \sinh\{\frac{|v^*_n (\tau) \cdot \tau|}{RT}\} \]
Static and Viscoelastic Testing/Modeling of LaRC SI

Tom Gates
January 4, 1996
Objectives:

- Measure effects of:
  1) Molecular Weight
  2) Cross-link Density

on the static and viscoelastic properties of LaRC SI

- Develop analytical models to account for these effects
  Elastic constants
  Elastic/plastic constants
  Fracture/strength
  Viscoelastic constants, physical aging
Static Properties: RT to \((T_g - 15^\circ C)\)

**Elastic**

*Youngs Modulus* \((E)\), *CTE*

*Poissons ratio* \((\nu)\)

*Shear Modulus* \(G = \frac{E}{2(1+\nu)}\)

**Plastic**

\[d\varepsilon_{ij}^p = d\lambda \frac{\partial J}{\partial \sigma_{ij}}\]

\[J = \frac{1}{3} \left[ r_{11}(\sigma_{11})^2 + (\sigma_{22})^2 + 2r_{12}\sigma_{11}\sigma_{22} + 2r_{66}(\sigma_{12})^2 \right]\]

*Effective Stress*  \(\bar{\sigma} = \sqrt{3J}\)

*Effective Plastic Strain*  \(\bar{\varepsilon}^p = \beta(\bar{\sigma})^\alpha\)
Geometry of Unit Cell

F = Fiber
M = Matrix

Two Regions: A, B

\[ x_1 \]
\[ x_2 \]
\[ x_3 \]
Micro-Model
Off-Axis, Test vs Predicted

IM7/5260
125°C

- 0° Test
- 15° Test
- 25° Test
- 30° Test
- Predicted

Stress (MPa)

Strain (mm/mm)

242
Micro-Model
Off-Axis, Test vs Predicted

IM7/5260
23°C

- 0° Test
- 15° Test
- 30° Test
- Predicted

Stress (MPa)

Strain (mm/mm)
Fracture/Strength  RT to (T_g -15\degree C)
  - Edge Notched tensile tests
  - Fracture surface morphology

Viscoelasticity, Physical Aging  (T_g -15\degree,20\degree,25\degree C)

\[ \varepsilon(t) = \int_{-\infty}^{t} S(t - \tau) \frac{d\sigma(\tau)}{d\tau} d\tau \]

Compliance  \[ S_y(t) = S_o e^{(\lambda/\eta)^\beta} \]

Effective Time  \[ d\lambda = a_{e(t)} dt \]
Free Volume Evolution During Aging

![Graph showing volume change with temperature, with a dashed line indicating the equilibrium line and a solid line showing the evolution of volume towards equilibrium at $T_g$.](image)
The Effects of Physical Aging on Creep Compliance

- Sequenced creep/recovery

For each sequence \( \frac{creep\ time}{aging\ time} = \frac{1}{10} \)

- Measure compliance shifts and shift rates due to aging

\[
\text{aging shift factor} \equiv -\log a
\]

\[
\text{aging shift rate} \equiv \mu = \frac{d \log(a_t)}{d \log(t_e)}
\]
K3B-Resin Creep 8-14
Log Compliance vs Log Time
Resin Specimen 72-3 Test Temperature 215C Stress 387.6 Psi

\[ t_e = 2 \text{ hr} \]
\[ xx \ t_e = 96 \text{ hr} \]
Figure XX: Long term 215°C resin data versus effective time theory prediction.
Figure XX: Long term 200°C resin data versus effective time theory prediction.
Figure: Comparison between resin and composite long term data at 215°C.
Computational Matl's. Related Issues

- Constituent Stiffness Properties $\not\Rightarrow$ Composite Properties
- Recovered Stiffness Properties $\not\Rightarrow$ Constituent Properties
- Can evaluate relative property differences between matl's.

- Unexplored material properties may correlate
  eg. Strength, CTE, Interface, ?

- Alternative constitutive relations may be required
  Need to expand beyond use of properties from macro level materials testing
Computational Materials aims to model and predict thermodynamic, mechanical, and transport properties of polymer matrix composites. This workshop, the second coordinated by NASA Langley, reports progress in measurements and modeling at a number of length scales: atomic, molecular, nano, and continuum. Assembled here are presentations on quantum calculations for force field development, molecular mechanics of interfaces, molecular weight effects on mechanical properties, molecular dynamics applied to poling of polymers for electrets, Monte Carlo simulation of aromatic thermoplastics, thermal pressure coefficients of liquids, ultrasonic elastic constants, group additivity predictions, bulk constitutive models, and viscoplasticity characterization.