

# SAND REPORT

SAND2001-3222

Unlimited Release

Printed October 2001

## Rapid Discovery of Materials

Douglas A. Loy, Eli E. Soto, and David R. Wheeler

Prepared by  
Sandia National Laboratories  
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,  
a Lockheed Martin Company, for the United States Department of  
Energy under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.



Sandia National Laboratories

***When printing a copy of any digitized SAND Report, you are required to update the markings to current standards.***

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

**NOTICE:** This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from  
U.S. Department of Energy  
Office of Scientific and Technical Information  
P.O. Box 62  
Oak Ridge, TN 37831

Telephone: (865)576-8401  
Facsimile: (865)576-5728  
E-Mail: [reports@adonis.osti.gov](mailto:reports@adonis.osti.gov)  
Online ordering: <http://www.doe.gov/bridge>

Available to the public from  
U.S. Department of Commerce  
National Technical Information Service  
5285 Port Royal Rd  
Springfield, VA 22161

Telephone: (800)553-6847  
Facsimile: (703)605-6900  
E-Mail: [orders@ntis.fedworld.gov](mailto:orders@ntis.fedworld.gov)  
Online order: <http://www.ntis.gov/ordering.htm>



SAND 2001-3222  
Unlimited Release  
Printed October 2001

## **Rapid Discovery of Materials**

Douglas A. Loy and Eli E. Soto  
Catalysis and Chemical Technologies Department

David R. Wheeler  
Micro-Total-Analytical Systems Department

Sandia National Laboratories  
P. O. Box 5800  
Albuquerque, NM 87185-0888

### **ABSTRACT**

The Rapid Discovery of Materials discretionary LDRD was a research project that in just five months, began an investigation into the application of combinatorial methods towards the discovery of a new class of removable polymers based on thermally labile chemical weak-links. Our goal was to find a way to speed up the process (relative to the lengthy synthesis/Characterization/thermal analysis procedure used in the past) by which the decomposition temperatures of removable polymers could be determined. In order to achieve this goal, new model compounds were prepared by Diels-Alder reactions and were characterized by X-ray diffraction and NMR spectroscopy. Polymers bearing reactive dienes and dienophiles were prepared and reacted to form the experimental material libraries attached to polymers as anchors. This effort has now reached the stage where thermogravimetric and mass spectrometric analyses can be used to determine the decomposition ranges for the different weak-links.

## **I. Preface**

This report summarizes the accomplishments and contributions of a discretionary LDRD whose purpose was to begin to explore the new and rapidly developing field of *Rapid Discovery* otherwise known as “combinatorial materials research.” In a few short months student employees from the University of New Mexico made admirable progress in initiating Sandia’s efforts towards a new paradigm of research where the major limitation on discovery is one’s imagination, not resources or time.

## **II. Acknowledgements**

This work was primarily based on the efforts of Eli Soto and Felicia Gonzalez. The project also benefited from the assistance of Ginger DeMarquis, Duane Schneider, Todd Alam, Mark Rodriguez, McKenzie Minke and the other members of the Hybrid Organic-Inorganic Materials Group in the Catalysts and Chemical Technologies Department, Organization 6245. It is also important to recognize Alan Sylwester who has been a tireless champion of Rapid Discovery at Sandia and abroad. Without Alan’s persistent efforts, neither the seed money to begin this research nor the results (described herein) would have materialized.

# Contents

I.	Preface.....	4
II.	Acknowledgements .....	4
III.	Summary .....	7
IV.	Introduction and Vision.....	7
V.	Rapid Discovery of Reversible Reactions.....	9
	i) Introduction	9
	ii) Model Compounds	11
	iii) Polymers	12
	iv) Future Work	14
VI.	References .....	14

**Figures**

Figure 1 ..... 8  
Figure 2 ..... 9  
Figure 3 ..... 9  
Figure 4 ..... 10  
Figure 5 ..... 11  
Figure 6 ..... 11  
Figure 7 ..... 12  
Figure 8 ..... 13  
Figure 9 ..... 13  
Figure 10 ..... 14

### III. Summary

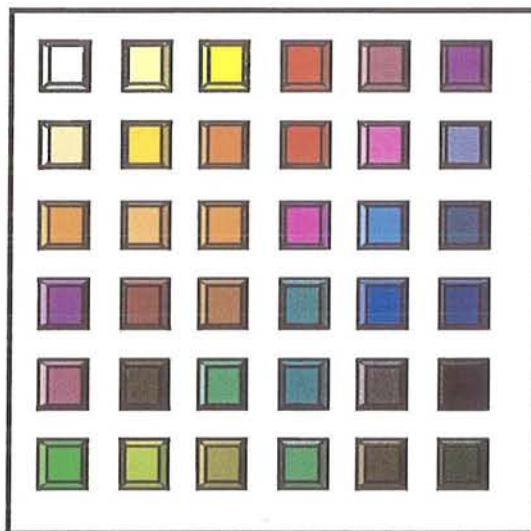
The Rapid Discovery of Materials discretionary LDRD was a research project that in just five months, began an investigation into the application of combinatorial methods towards the discovery of a new class of removable polymers based on thermally labile chemical weak-links. Our goal was to find a way to speed up the process (relative to the lengthy synthesis/Characterization/thermal analysis procedure used in the past) by which the decomposition temperatures of removable polymers could be determined. In order to achieve this goal, new model compounds were prepared by Diels-Alder reactions and were characterized by X-ray diffraction and NMR spectroscopy. Polymers bearing reactive dienes and dienophiles were prepared and reacted to form the experimental material libraries attached to polymers as anchors. This effort has now reached the stage where thermogravimetric and mass spectrometric analyses can be used to determine the decomposition ranges for the different weak-links.

### IV. Introduction and Vision

*Rapid Discovery of Materials* is a term we coined for what has been called Combinatorial Materials Research since its first use by Professor Peter Schultz in the early 1990's [1]. The new term was coined to describe what is becoming an increasingly important and more useful theme within combinatorial research that focuses on highly parallel methodologies. This distinction is important because the random generation of material libraries is generally not as easily accomplished as with the solid state synthesis of biologically active molecules. More importantly, screening of material libraries generated in combinatorial materials research is difficult, highlighted by the fact that screening techniques with the universality of *in vivo* screening of drugs do not presently exist. We recognized early on that Sandia National Laboratories possessed a unique set of capabilities that positioned this organization as a potential leader in the development of new highly parallel analytical instrumentation that could be used for *all* combinatorial research and in the search for (and optimization of) materials that are important to Sandia's internal missions. Furthermore, we recognized the potential for rapidly harvesting information about vast families of complex materials that could be used to support semi-empirical modeling efforts.

Combinatorial materials research historically requires that a large number of compounds or materials be rapidly made—generally in a single reaction vessel [2-8]. While this would seem to be a foolish exercise and a waste of materials, it was recognized that if the analytical screen could be invented that would allow single library members whose chemical and physical properties met some desirable criteria to be identified and quantified then combinatorial screening of materials would become a power tool in the materials scientist's arsenal. A number of combinatorial techniques have been developed for the creation of libraries of chemicals with biological activities. The chemicals are identified through a variety of labeling schemes after being screened for activity through the response of a microorganism. This is merely an extension of how biologicals and naturally occurring chemicals are screened as antibiotics, and it is the same method by which penicillin was discovered to have antibacterial properties by Fleming in the 1940's [9].

After successful application to pharmaceuticals discovery for five years, an adaptation was created for the discovery of phosphors and fluorescent ceramics [1]. In this method a library of materials was prepared by the gas phase deposition of a number of metal oxide precursors through masks onto a silicon wafer (**Figure 1**). By moving the mask or using different masks, a library of spatially resolved materials were prepared and thermally annealed before screening visually for fluorescence. In this first experiment, the researchers at Lawrence Berkeley National Laboratory were able to identify new material compositions with improved fluorescence characteristics.



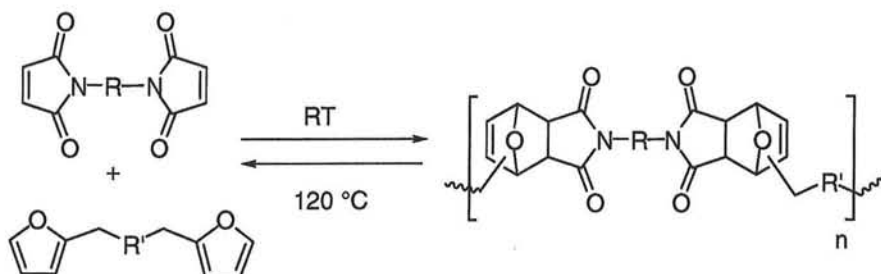
**Figure 1.** A drawing of how a combinatorial library of materials would look like when prepared by Schultz's technique of depositing different combinations through masks [1].

Since then, a number of companies and universities have developed strong combinatorial research programs for discovering new catalysts [10-17] and new materials [17-32]. Sandia National Laboratories' microChemLab on a chip was identified by a number of these companies as being a solution to the analytical bottleneck that hampers many combinatorial strategies. We have developed a vision for Rapid Discovery that encompasses the entire combinatorial process from library preparation, to screening, to informatics (data mining) and could potentially revolutionize the way materials are discovered. This vision includes the development of the microChemLab on a chip into highly parallel arrays that would speed the screening of small molecules by orders of magnitude. It also includes the development surface acoustic wave (SAW) devices as a general analytical platform for rapid discovery of new polymers, encapsulants, antioxidants, catalysts for petrochemical applications and for chemical processes and polymerization reactions [33]. The project described in this report was designed to evaluate rapid discovery methodologies in preparation for a lab-wide Rapid Discovery Initiative.

The materials project chosen for this LDRD was the rapid screening of reversible reactions that can be used in plastics to make them thermally removable [34] or more permeable (**Figure 2**). In this project, significant progress was made, though there was



insufficient time (< 5 months) and resources to complete the work. Both project are still being pursued.

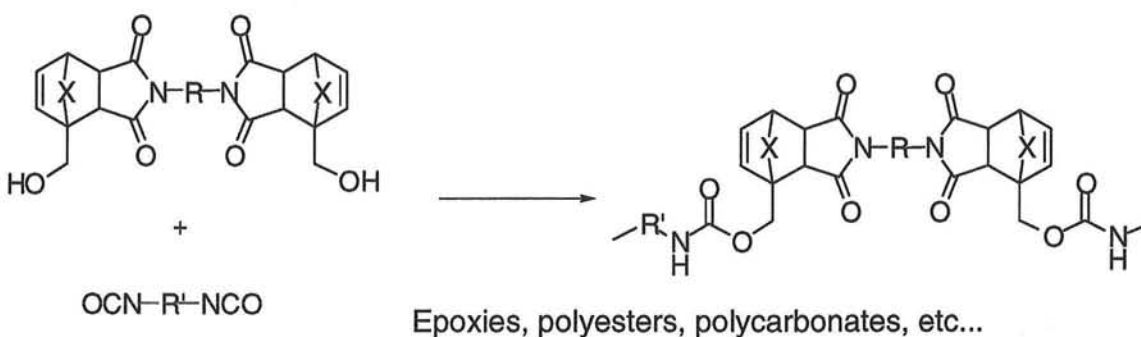


**Figure 2.** Polymers that form at room temperature by a Diel-Alder polymerization reaction and decompose at temperatures over 100 °C by the retro Diels-Alder reaction.

## V. Findings: Rapid Screening of Reversible Reactions

### Introduction

Reactions that can be made to reverse with the application of heat or light are attractive for forming recyclable materials or for making materials with thermoset-like physical properties that can be removed like a thermoplastic. There are a number of thermally and photochemically reversible reactions that have been used to make thermally or photochemically reversible gels from polymers [34]. We have been interested for over six years in the preparation of network, sol-gel like materials that would form under thermodynamic conditions. It was based on this idea that Sandia's Removable Encapsulant Program began [35]. The removable encapsulants are based on epoxy- or urethane polymers with Diels-Alder substructural weak-links as part of the polymer architecture (**Figure 3**).



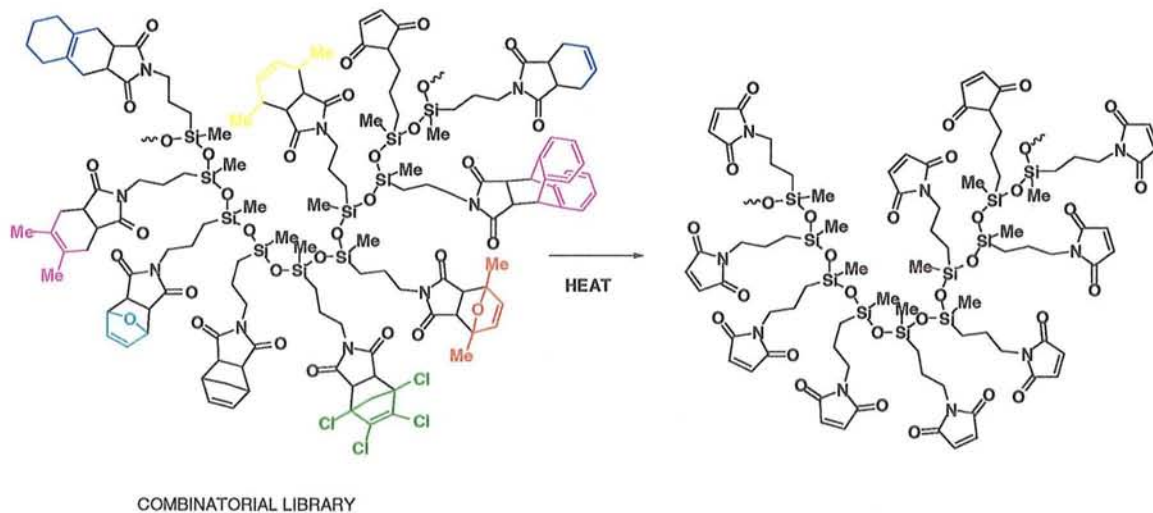
**Figure 3.** Formation of polyurethane with Diels-Alder weak link built into polymer backbone.

The Diels-Alder adduct we chose to be this thermal weak-link was the product of the Diels-Alder reaction between a substituted furan and a substituted maleimide which can

proceed at room temperature, but is often performed at 60 °C (Figure 2). By preparing monomers with two or more maleimides and two or more furans, it is readily possible to form polymers. When the resulting polymers are heated above 100 °C, the equilibrium of the Diels-Alder reaction shifts to favor the free diene (furan) and dienophile (maleimide) causing the polymer to break apart into oligomeric pieces that can be readily removed.

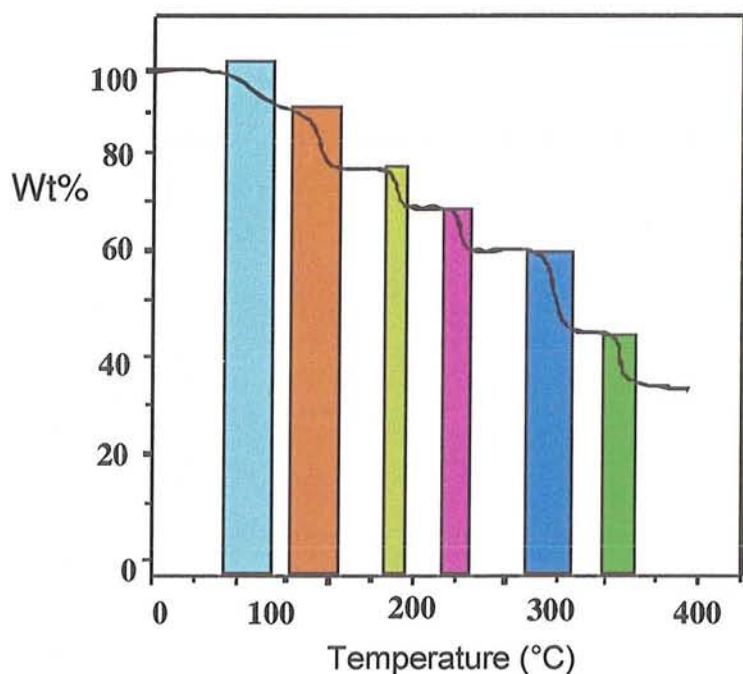
While this concept is very attractive and has numerous potential commercial applications, it would be useful to have a number of *different* Diels-Alder weak-links, all with distinct decomposition temperatures, from which to choose. However, the temperatures at which Diels-Alder reactions begin to reverse are not well known outside of a few, like the furan-maleimide Diels-Alder adducts. Determining what the decomposition temperatures are would require tens if not hundreds of synthetic polymers requiring many man-years to prepare. (Note: Computational modeling can give some insight into the thermodynamics of the Diels-Alder reaction, but does not give any insight to how kinetic stabilization would affect the onset of decomposition.)

In this project, we describe how a combinatorial library of Diels-Alder adducts can be prepared from a polymer bearing a single type of diene or dienophile (Figures 4). The basic concept is simple. For the dienophile-functionalized polymer: The dienophile groups on the polymer will react with those dienes for which the Diels-Alder reaction is favorable at the conditions used to afford a polymer with a variety of Diels-Alder adducts hanging as pendent groups. The polymer can be completely purified by capitalizing on the lower solubility of polymers and carrying out a series of precipitations.



**Figure 4.** Combinatorial library of Diels-Alder adducts based on maleimide functionalized polysilsesquioxane.

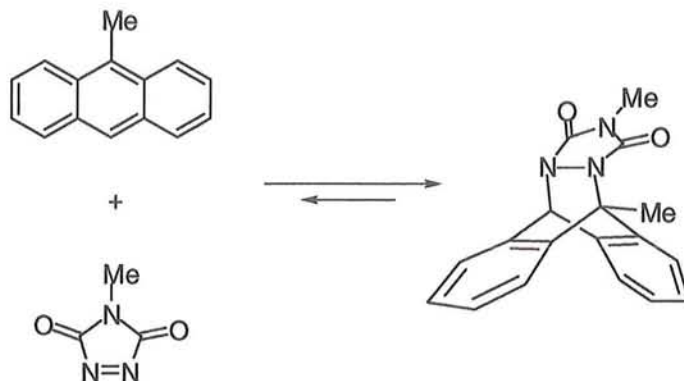
The effective decomposition temperature (range) of each individual Diels-Alder adduct can be determined by slowly heating the polymer in a thermogravimetric analyzer-mass spectrometer, or in a thermogravimetric analyzer-infrared spectrometer, and correlating temperature and mass loss with the thermally liberated dienes (Figure 5). An identical procedure can be carried out by forming the Diels-Alder adducts between a polymer functionalized with a diene and a library of dienophiles.



**Figure 5.** Cartoon showing how mass spec/tga will be used to screen library. The mass spectrometer will be used to identify the dienes or dienophiles as they reach the temperature ranges where the retro Diels-Alder reactions occur.

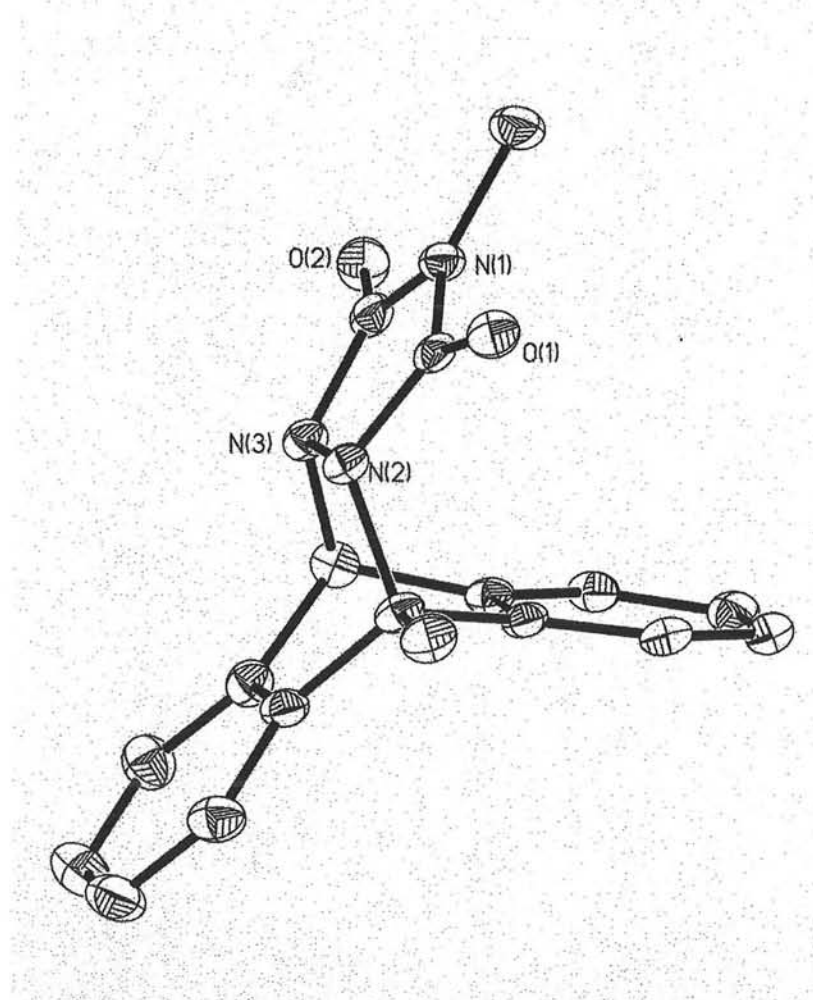
#### Model Compounds

Because only small amounts of each Diels-Alder adduct would be present in each polymer, model compounds were synthesized to permit exact structural characterization with X-ray diffraction and NMR spectroscopy. One Diels-Alder adduct model compound prepared from anthracene and the diaza analog of maleimide, N-Methyl-1,3,4-triazoline-2,5-dione, is shown in **Figure 6**.



**Figure 6.** Preparation of Diels-Alder model compound (right) through the reaction of anthracene and N-Methyl-1,3,4-triazoline-2,5-dione.

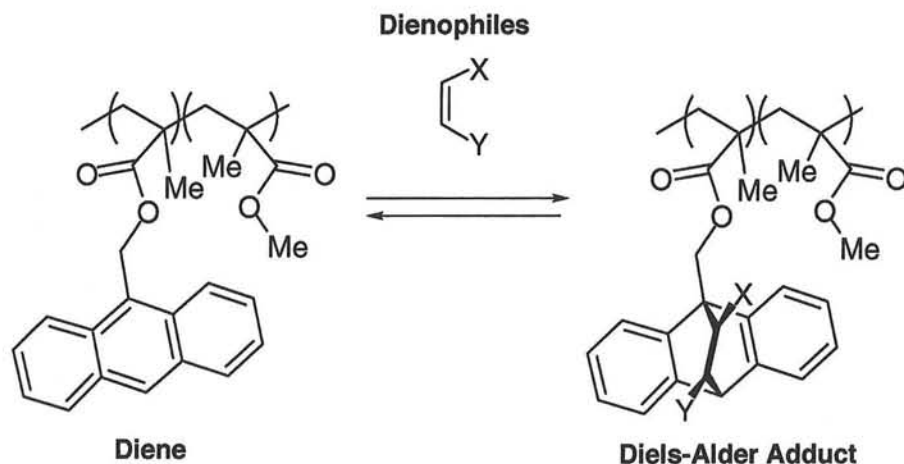
An X-ray diffraction structure of the Diels Alder adduct is shown in **Figure 7**.



**Figure 7.** X-ray crystal structure of Diels Alder adduct of N-Methyl-1,3,4-triazoline-2,5-dione with 9-methylantracene.

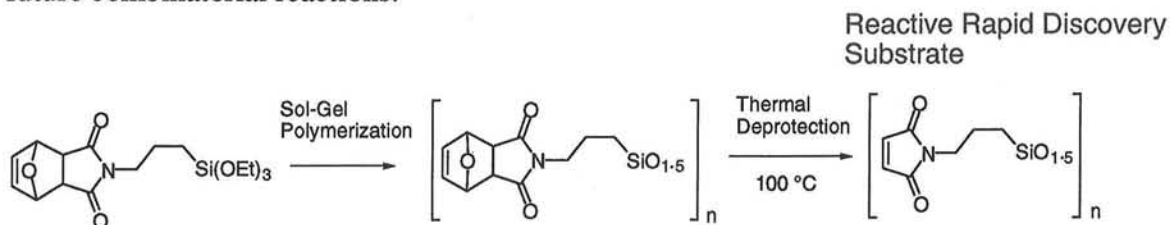
### Polymers

There were several different polymeric platforms that could be used for the rapid screening. We are looking for, and have prepared, three different systems to which either diene or dienophile groups can be appended. The first is based on a polymethylmethacrylate. The functional group can be readily attached to the polymer by replacing some of the methyls with the diene or dienophile derivatized as an alcohol (**Figure 8**). For our first functionalized polymer we polymerized 9-anthracenylmethylmethacrylate with methylmethacrylate under free radical polymerization conditions.



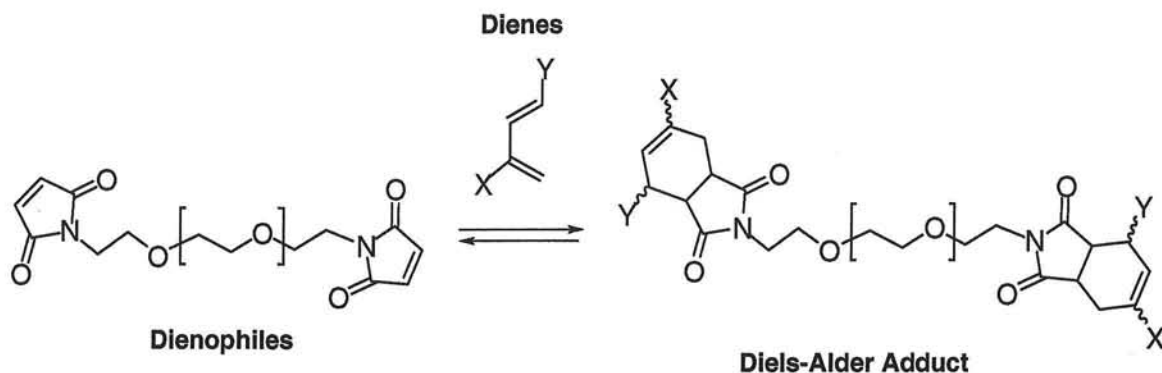
**Figure 8.** Polymethylmethacrylate based combinatorial platform for screening Diels-Alder adducts thermal decomposition.

The second polymer was a polysilsesquioxane with a pendent maleimide group (**Figure 9**). Since the maleimide is a strong Michael acceptor and reacts with water, we protected the group as a Diels-Alder adduct. Once the monomer is hydrolyzed and condensed to a polymer, it can be heated to reverse the Diels-Alder reaction and free the dienophile for future combinatorial reactions.



**Figure 9.** Sol-gel polymerization of Diels-Alder adduct protected maleimide-functionalized triethoxysilane.

The last polymer system is based on a commercially available polyethyleneoxide that is end-functionalized with maleimide groups (**Figure 10**). This class of polymer is used in combinatorial drug synthesis and it is very attractive because it readily precipitates to allow purification. However, with only 1-2 maleimides per polymer chain, the number of Diels-Alder adducts per gram drops is much less than the polyacrylate and the polysilsesquioxane systems described above.



**Figure 10.** Maleimide end-functionalized polyethylene oxide as a polymeric support for Diels-Alder adducts.

In the final stage of the project, we reacted the anthracenyl-functionalized polyacrylate with four different dienophiles. The other two polymers will be functionalized shortly.

#### Future Work

The next step is to perform the thermal gravimetric analyses on the polymers and determine if we can resolve the temperature ranges where distinct dienophiles or dienes are liberated. Part of this work will be looking to evaluate the optimum polymeric platform. Once the decomposition ranges are established we will synthesize polymers with some of the weak-links built in to determine if the decomposition ranges are consistent with the values determined by the combinatorial screen.

#### **VI. References**

- 1) "A combinatorial approach to materials discovery." Xiang, X.-D.; Sun, Xiaodong; Briceno, Gabriel; Lou, Yulin; Wang, Kai-An; Chang, Hauee; Wallace-Freedman, William G.; Chen, Sung-Wei; Schultz, Peter G. *Science* **1995**, *268*, 1738-40.
- 2) "Combinatorial chemistry and new drugs." Plunkett, Matthew J.; Ellman, Jonathan A. *Sci. Am.* **1997**, *276*, 68-73.
- 3) "Spatially addressable combinatorial libraries." Pirrung, Michael C. *Chem. Rev.* **1997**, *97*, 473-488.
- 4) "The "One-bead-one-compound combinatorial library method." Lam, Kit S.; Lebl, Michal; Krchnak, Viktor. *Chem. Rev.* **1997**, *97*, 411-448.
- 5) "Directed combinatorial chemistry." Hogan, Joseph C., Jr. *Nature* **1996**, *384*, 17-19.
- 6) "Synthesis and Applications of Small Molecule Libraries." Thompson, Lorin A.; Ellman, Jonathan A. *Chem. Rev.* **1996**, *96*, 555-600.
- 7) "Soluble polymers: New options in both traditional and combinatorial synthesis." Harwig, Curtis W.; Gravert, Dennis J.; Janda, Kim D. *Chemtracts* **1999**, *12(1)*, 1-26.
- 8) "The combinatorial chemistry of nature." Verdine, Gregory L. *Nature* **1996**, *384*, 11-13.
- 9) "Early discoveries in the penicillin series." Nayler, John H. C. *Trends Biochem. Sci.* **1991**, *16*, 195-7.

- 10) "Combinatorial chemistry in heterogeneous catalysis: a new scientific approach or "the king's new clothes". Schlogl, Robert. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 2333-2336.
- 11) "Infrared thermographic screening of combinatorial libraries of heterogeneous catalysts." Bergbreiter, David E. *Chemtracts* **1997**, *10*, 683-686.
- 12) "Rapid screening of biocatalysts." Fenniri, Hicham. *Chem. Sci., CHEMTECH* **1996**, *26*, 15-25.
- 13) "Speeding catalyst discovery and optimization." Crabtree, Robert H. *CHEMTECH* **1999**, *29*, 21-26.
- 14) "Efficient assays for combinatorial methods for the discovery of catalysts." Bein, Thomas. *Angew. Chem., Int. Ed. Engl.* **1999**, *38*, 323-326.
- 15) "Application of combinatorial technologies for catalyst design and development." Gennari, Fabiana; Seneci, Pierfausto; Miertus, Stanislav. *Catal. Rev. - Sci. Eng.* **2000**, *42*, 385-402.
- 16) "Combinatorial chemistry, high-speed screening and catalysis" Pescarmona, Paolo P.; Van der Waal, Jan C.; Maxwell, Ian E.; Maschmeyer, Thomas. *Catal. Lett.* **1999**, *63*, 1-11.
- 17) "Combinatorial libraries of transition-metal complexes, catalysts and materials." Francis, Matthew B.; Jamison, Timothy F.; Jacobsen, Eric N. *Curr. Opin. Chem. Biol.* **1998**, *2*, 422-428.
- 18) "Combinatorial heterogeneous catalysis-a new path in an old field." Senkan, Selim, *Angew. Chem., Int. Ed. Engl.* **2001**, *40*, 312-329.
- 19) "Combinatorial approaches to materials science." Schultz, Peter G.; Xiang, Xiao-Dong. *Curr. Opin. Solid State Mater. Sci.* **1998**, *3*, 153-158.
- 20) "Combinatorial approach in search of luminescent materials." Sun, Ted X.; Xiang, X.-D.; Srivastava, Alok M. *Proc. - Electrochem. Soc.* **2000**, *99-40* (Physics and Chemistry of Luminescent Materials), 50-55.
- 21) "Combinatorial chemistry and combinatorial technologies: principles and applications." Fassina, Giorgio; Miertus, Stanislav. *Comb. Chem. Technol.* **1999**, 1-5.
- 22) "Combinatorial materials synthesis and screening: an integrated materials chip approach to discovery and optimization of functional materials." Xiang, X.-D. *Annu. Rev. Mater. Sci.* **1999**, *29* 149-171.
- 23) "Combinatorial approaches to materials discovery." McFarland, Eric W.; Weinberg, W. Henry. *Trends Biotechnol.* **1999**, *17*, 107-115.
- 24) "Automated Electrochemical Analysis with Combinatorial Electrode Arrays." Sullivan, Melani G.; Utomo, Henry; Fagan, Paul J.; Ward, Michael D. *Anal. Chem.* **1999**, *71*, 4369-4375.
- 25) "Combinatorial synthesis and high throughput evaluation of functional oxides. An integrated materials chip approach." Xiang, X.-D. *Mater. Sci. Eng., B* **1998**, *B56*, 246-250.
- 26) "It's a materials world." Xiang, Xiao-Dong. *Chem. Ind.* **1998**, *19*, 800-802.
- 27) "Combinatorial synthesis of advanced ceramic materials." Siegel, Andre. *Can. Ceram.* **1998**, *67*, 17-21.
- "Combinatorial materials science: paradigm shift in materials discovery and optimization." Engstrom, James R.; Weinberg, W. Henry. *AIChE J.* **2000**, *46*, 2-5.

- 28) "Functional materials design for the new millennium: updating the rational strategy and enabling tools." Bedard, Robert L. *AIChE J.* **1999**, *45*, 2474-2476.
- 29) "Combinatorial chemistry of materials, polymers and catalysts." Maier, W. F.; Kirsten, G.; Orschel, M.; Weiss, P.-A.; Holzwarth, A.; Klein, J. *Macromol. Symp.* **2001**, *165*(Developments in Polymer Synthesis and Characterization), 1.
- 30) "New materials for a new millennium." Cabrera, Carlos A. *Hydrocarbon Eng.* **2000**, *5*, 44-45.
- 31) "Combinatorial materials science and catalysis." Jandeleit, Bernd; Schaefer, Dieter J.; Powers, Timothy S.; Turner, Howard W.; Weinberg, W. Henry. *Angew. Chem., Int. Ed.* **1999**, *38*, 2494-2532.
- 32) "Automatic determination of phase diagrams." Weitkamp, Jens; Hunger, Michael. *Chem. Unserer Zeit* **1998**, *32*, 83.
- 33) "Correlation of surface acoustic wave device coating responses with solubility properties and chemical structure using pattern recognition." Ballantine, David S., Jr.; Rose, Susan L.; Grate, Jay W.; Wohltjen, Hank *Anal. Chem.* **1986**, *58*, 3058-66.
- 34) "Thermally reversible polymer linkages. II. Linear addition polymers." Wagener, K. B.; Engle, L. P. *J. Polym. Sci., Part A: Polym. Chem.* **1993**, *31*, 865-75.
- 35) Removable Encapsulants SAND report



Distribution copies to:

10	MS 0888	Douglas A. Loy, 6245
1	MS 0734	Larry Bustard, 6245
1	MS 0741	Margie Tatro, 6200
1	MS 0188	Chuck Meyers, 1030
1	MS 9018	Central Technical Files, 8945-1
2	MS 0899	Technical Library, 9616
1	MS 0612	Review and Approval Desk, 9612 For DOE/OSTI
1	MS 0161	Patents and Licensing Office, 11500