the prediction of the model. A typical result is presented in Figure 1b, which is obtained when a sodium sulfide solution is introduced into a hydrogen peroxide solution already present in the flask. Note that the roles of the reactants are not symmetric; no oscillatory conditions could be found in which the $H_2O_2$ solution was added to the sulfide solution. This asymmetry appears to be a general feature of oscillatory semibatch systems.

The well-known Landolt reaction, the iodate oxidation of hydrogen sulfite, is an important component process of a number of pH oscillators. When the Landolt reaction takes place in the presence of thiosulfate, pH-regulated oscillations can occur both in CSTR[13] and in batch.[14] However, the batch oscillation is strongly damped, and only two or three periods can be observed. Under semibatch conditions, we are able to obtain damped oscillation with many more cycles of oscillation (Figure 1c). The period of the oscillations in this reaction is extremely sensitive to the temperature in the CSTR mode.[13] This unusual sensitivity is not observed either in batch or in semibatch. Further semibatch investigation of the temperature sensitivity of this reaction may lead to an explanation of the peculiar temperature effect.

While the potential of the semibatch reactor for studies of nonlinear chemical dynamics remains largely unexplored, we believe that these initial investigations as well as those of refs 4–8 suggest that this technique merits further investigation as a tool in the arsenal of the chemical dynamicist.

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## The First Unambiguous Synthesis of Poly(alkyl/aryloxothiazenes). A Novel Route to Precursors and Synthesis of Polymers

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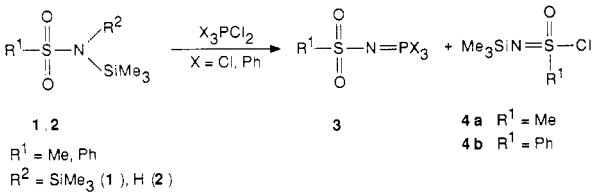
Recent years have seen a resurgence in interest in inorganic polymers. One reason for this is that several existing inorganic polymers, and their hybrids with organic polymers, possess properties not exhibited by conventional carbon-based macromolecules. The synthesis of poly(oxothiazenes),[1] polymers with an alternating sulfur(VI)–nitrogen backbone, has been reported sporadically by various groups since the early 1960s.[2-9] However, the polymers in several of these reports either were low molecular weight oligomers or were simply inferred without substantiation of their polymeric identity. We now report a general synthesis of linear, high molecular weight alkyl and aryl poly(oxothiazenes), $[N{=}S(O)R]_n$, in two steps from N-silylated sulfonamides.[10] The synthesis of *N*-silylsulfonimidates[11] and their condensation to poly(oxothiazenes) in a manner analogous to the condensation of *N*-silylphosphoranimines to polyphosphazenes[12] are shown in Schemes I and II.

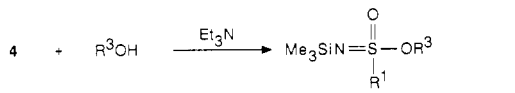
**Scheme I**




**1**, **2**
$R^1$ = Me, Ph
$R^2$ = $SiMe_3$ (**1**), H (**2**)

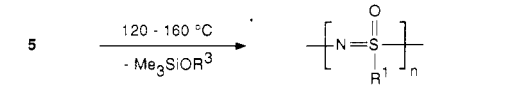
**3**

**4a** $R^1$ = Me
**4b** $R^1$ = Ph

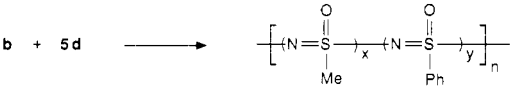



**5a** $R^1$ = Me, $R^3$ = $CH_2CF_3$
**5b** $R^1$ = Me, $R^3$ = Ph
**5c** $R^1$ = Ph, $R^3$ = $CH_2CF_3$
**5d** $R^1$ = Ph, $R^3$ = Ph

**Scheme II**




**6a** $R^1$ = Me
**6b** $R^1$ = Ph




**7**
x = y

**Table I.** Molecular Weight and $T_g$ of Poly(oxothiazenes)

| sulfonimidate | polymer | temp, °C | mol wt[a] $M_w$ | mol wt[a] $M_n$ | $T_g$, °C |
|---|---|---|---|---|---|
| **5a** | **6a** | 160 | 51 812 | 5898 | 55–65 |
| **5b** | **6a** | 120 | 408 982 | 31 671 | – |
| **5c** | **6b** | 170 | 10 471 | 3509 | – |
| **5d** | **6b** | 120 | 194 614[b] | 138 116 | 85 |
| | | | 14 110 | 12 242 | |
| **5b + 5d** | **7** | 140 | 256 000 | 36 630 | 72 |

[a] Molecular weights (in DMF) are relative to polystyrene and are, therefore, only estimates. [b] Bimodal distribution.

The conversion of N-silylated sulfonamides (**1**, **2**) to sulfonimidoyl chlorides **4** was accomplished via reaction with halophosphoranes of the type $X_3PCl_2$. The course of the reaction was found to be dependent on the polarity of the solvent used and the steric bulk of the phosphorus reagent. While the bis(silyl) sulfonamide **1a** ($R^1$ = Me) and $PCl_5$ in refluxing $CCl_4$ yielded only **3** (evidenced by a S–Me doublet due to phosphorus coupling in the $^1H$ NMR spectrum), the same reaction in $CHCl_3$ produced a 1:1 mixture of **3** and *N*-(trimethylsilyl)methanesulfonimidoyl chloride (**4a**). The downfield $^1H$ NMR chemical shift ($\delta$ 3.5) of

(1) Early nomenclature described these polymers as "poly(oxosulfurnitrides)". However, we have chosen to introduce the "oxothiazene" nomenclature for the repeat unit $[N{=}S(O)R]$ consisting of a sulfur(VI)–nitrogen skeletal unit with oxygen as a "fixed" substituent on sulfur because of close structural similarity with the well-recognized phosphazene unit $[N{=}PR_2]$, and because of reasonings similar to those used by Allcock for his preference of the phosphazene nomenclature, as discussed in the following: Allcock, H. R. *Phosphorus-Nitrogen Compounds*: Academic Press: New York, 1972; pp 7–13.
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the S-Me group in **4a** was comparable with reported values for similar compounds.[8] With the bulkier $Ph_3PCl_2$[13] (in place of $PCl_5$) in $CHCl_3$, **1a** yielded only **4a** at 10-15 °C. Further, even monosilyl sulfonamides **2** were found to react cleanly with $Ph_3PCl_2$ near 0 °C, in the presence of $Et_3N$, to produce only **4**. Upon standing at room temperature, the sulfonimidoyl chlorides slowly decomposed, but they were stable in solution for several hours at 0 °C.

The sulfonimidoyl chlorides **4** were then allowed to react in situ at 0 °C with a mixture of alcohol and triethylamine to yield the corresponding sulfonimidates **5** as distillable liquids.[14] The 2,2,2-trifluoroethyl sulfonimidates exhibited diastereotopic $CH_2CF_3$ protons in the $^1H$ NMR spectra, thereby aiding their identification by confirming the chirality at sulfur.

When heated in evacuated Pyrex ampules between 120 and 160 °C, the sulfonimidates **5** condensed over 3-6 days, producing silyl ether, the solid homopolymers **6a** and **6b**, and copolymer **7**. While some irreproducibility was observed in the polymerization behavior of the 2,2,2-trifluoroethyl sulfonimidates, the phenyl sulfonimidates always cleanly produced polymer and silyl ether. Polymer **6a** was purified by precipitation from DMF solution into toluene, while **6b** and **7** were precipitated into hexanes from dichloromethane solution and chloroform solution, respectively.

The polymeric nature of **6a**, **6b**, and **7** was determined by gel permeation chromatography (GPC), which showed relatively high molecular weights for the polymers derived from the phenyl sulfonimidates, but lower molecular weights for those derived from the 2,2,2-trifluoroethyl sulfonimidates (Table I). Additional characterization was obtained by elemental analysis, by $^1H$ and $^{13}C$ NMR[15] spectroscopy for **6a**, and by differential scanning calorimetry (DSC) (Table I). The striking feature in the DSC of **6a** is a $T_g$ in the range 55-65 °C, which contrasts sharply with the corresponding -46 °C of the analogous poly(dimethylphosphazene).[12] Polymer **6a** is soluble in DMF, DMSO, and nitromethane, but insoluble in hydrocarbons, ethers, nitriles, and chlorinated hydrocarbons.

Further work on the novel conversion of silyl sulfonamides to sulfonimidoyl halides and the synthesis of poly(oxothiazenes) from sulfonimidates is in progress in our laboratories, and details on these will appear in future publications.

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(14) Conversion of **2** to **5** was carried out by addition of $Et_3N$ to $Ph_3PCl_2$ at 0 °C, followed by addition of **2** at -78 °C, warming to 0 °C till the mixture became clear, and then addition of a mixture of alcohol and $Et_3N$ at 0 °C. For sulfonimidate **5a**: yield 73%; bp 77-78 °C/7.7 mm; $^1H$ NMR (in benzene) $\delta$ 0.28 (s, $Me_3Si$), 2.35 (s, Me-S, 2.98 in $CDCl_3$), 3.92 (m, $CH_2CF_3$, diastereotopic protons); $^{13}C$ NMR (in $CDCl_3$) $\delta$ 1.8 (s, $Me_3Si$), 43.2 (s, Me-S), 63.7 (q, $CH_2CF_3$, $^2J_{FC}$ = 36.9 Hz), 122.9 (q, $CH_2CF_3$, $^1J_{FC}$ = 278.1 Hz). Anal. Calcd: C, 29.14; H, 5.66; N, 5.62. Found: C, 29.01; H, 5.47; N, 5.65. For **5b**: yield 40-50%; bp 83-85 °C/0.25 mm; $^1H$ NMR (in $CH_2Cl_2$) $\delta$ 0.03 (s, $Me_3Si$), 3.05 (s, Me-S), 7.1-7.6 (m, $OC_6H_5$); $^{13}C$ NMR (in $CDCl_3$) $\delta$ 1.7 ($Me_3Si$), 42.6 (Me-S), 150.2 (ipso-C), 122.9 (*o*-C), 129.6 (*m*-C), 126.4 (*p*-C). Anal. Calcd: C, 49.35; H, 7.04; N, 5.75. Found: C, 49.52; H, 7.06; N, 5.80. For **5c**: yield 27%; bp 84-86 °C/0.7 mm; $^1H$ NMR (in benzene) $\delta$ 0.37 (s, $Me_3Si$), 3.87 (m, $CH_2CF_3$, diastereotopic protons), 7.4-8.0 (m, $C_6H_5$, in $CH_2Cl_2$); $^{13}C$ NMR (in $CDCl_3$) $\delta$ 1.8 (s, $Me_3Si$), 64.2 (q, $CH_2CF_3$, $^2J_{FC}$ = 36.9 Hz), 122.5 (q, $CH_2CF_3$ $^1J_{FC}$ = 277.9 Hz), 139.5 (ipso-C), 127.6 (*o*-C), 129.1 (*m*-C), 133.1 (*p*-C). Anal. Calcd: C, 42.43; H, 5.18; N, 4.50. Found: C, 41.90; H, 5.16; N, 4.59. For **5d**: yield 18%; bp 113-120 °C/0.06 mm: $^1H$ NMR (in $CDCl_3$) $\delta$ 0.29 (s, $Me_3Si$), 6.9-7.9 (m, S-$C_6H_5$ and O-$C_6H_5$); $^{13}C$ NMR (in $CDCl_3$) $\delta$ 2.0 ($Me_3Si$), [S-$C_6H_5$; 140.1 (ipso-C), 127.8 (*o*-C), 128.5 (*m*-C), 132.6 (*p*-C)], [O-$C_6H_5$; 150.7 (ipso-C), 122.9 (*o*-C), 129.1 (*m*-C), 126.1 (*p*-C)]. Anal. Calcd: C, 58.98; H, 6.27; N, 4.59. Found: C, 59.49; H, 6.32; N, 4.39. Slight condensation, producing the relatively high boiling $Me_3SiOPh$, always occurred during distillation of phenyl sulfonimidates. All NMR chemical shifts are relative to the solvents shown in parentheses.

(15) For **6a**: $^1H$ NMR (in $d_6$-DMSO) $\delta$ 3.40-3.56 (br, S-Me); $^{13}C$ NMR (in $d_6$-DMSO) $\delta$ 46.4 (S-Me). Anal. Calcd: C, 15.58; H, 3.92; N, 18.17. Found: C, 16.07; H, 3.83; N, 18.32. Once dissolved in DMF, the polymer retained 2-3% of the solvent, which was extremely difficult to remove even after precipitation and repeated vacuum drying at 100-135 °C. Reprecipitation from $MeNO_2$ into toluene was finally used to obtain a sample for microanalysis. For **6b**: Anal. Calcd: C, 51.78; H, 3.62; N, 10.06. Found: C, 51.97; H, 3.77; N, 9.99. For **7**: Anal. Calcd (for 1:1 copolymer): C, 38.87; H, 3.73; N, 12.95. Found: C, 39.89; H, 4.03; N, 12.55.

# Biosynthetic Incorporation of Labeled Tetraketide Intermediates into Dehydrocurvularin, a Phytotoxin from *Alternaria cinerariae*, with Assistance of $\beta$-Oxidation Inhibitors

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Microorganisms produce a host of commercially important natural products by the polyketide biosynthetic pathway.[1] Isotopic labeling studies,[2] genetic investigations,[3] and experiments with mutants[4] and enzyme inhibitors[5] support the current view that polyketide formation occurs with complete construction of a functionalized carbon skeleton from short fatty acids by an organized enzyme complex. In some cases, further localized transformations (e.g., oxidation, alkylation) involving separate enzymes follow this construction of the parent molecule. The assembly process is similar to fatty acid biosynthesis, but reductive steps are bypassed in particular cycles to lead to incorporation of keto, hydroxy, or olefinic functionality in the growing polyketide chain.[3c] With the exception of polyketide synthases that form simple aromatic compounds (e.g., 6-methylsalicylic acid),[6] the cell-free production of complex polyketides or isolation of their assembly enzymes has not been reported. Intact incorporations of correctly functionalized di- and triketides as their *N*-acetylcysteamine (NAC) thiolesters into *propionate*-derived metabolites such as erythromycin,[7] tylactone,[8] nargenicin,[7b,9] and nonactin[10] provide key support for the proposed biosynthetic pathways and structures of enzyme-bound intermediates. Unfortunately, such experiments are generally plagued by rapid degradation of the labeled precursors to acetate (or propionate) by efficient $\beta$-oxi-

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