[115 °C (1 mm)] gave isoxazolidine **12** as a yellow oil (1.06 g, 92%). On the basis of GC (OV-101/130 °C) and NMR analysis the product consisted of one isomer (retention time 3.4 min) which was assigned the trans configuration (**12b**): ^{1}H NMR ($CDCl_3$) 1.21 (t, 3 H, J = 7 Hz), 1.29 (t, 3 H, J = 7 Hz), 2.55 (dd, 1 H, J = 8, 8 Hz), 2.71 (ddd, 1 H, J = 5, 8, 8 Hz), 2.95 (s, 3 H), 3.48 (dq, 1 H, J = 7, 10 Hz), 3.75 (dd, 1 H, J = 8, 8 Hz), 3.81 (dq, 1 H, J = 7, 10 Hz), 4.21 (q, 2 H, J = 7 Hz), 5.20 (d, 1 H, J = 5 Hz);[18] IR (CCl_4) 3000–2800 (s), 1750–1700 (vs), 1450–1400 (s), 1200–1150 (vs), 1100–1000 (vs); mass spectrum, m/z (relative intensity) 203 (M^+, 5), 157 (5), 130 (100), 102 (17), 84 (24).

General Procedure for High-Pressure Reaction of Nitrones and Ethyl Vinyl Ether (3). A solution of the nitrone in ethyl vinyl ether (~0.3 M) was sealed in Teflon tubing and placed in the high-pressure autoclave. The reaction vessel was pressurized and heated (when required). After the autoclave was cooled (where appropriate), the pressure was relieved, and the vessel was removed. Purification and analysis of the product mixture was accomplished as outlined above. Cycloadducts **5ab**, **8a**, **8b**, **10**, and **12b** were obtained from the respective nitrones in the yields described in the Table.

Isoxazolidines 7a,b. High-Pressure Conditions. A solution of nitrone **1** (0.102 g, 0.75 mmol) and vinylidene carbonate (0.130 g, 1.5 mmol) in 5 mL of CH_2Cl_2 was sealed in teflon Tubing and pressurized to 2000 kbar for 48 h. Purification of the reaction mixture by column chromatography (CH_2Cl_2) yielded isoxazolidine **7a** (17%), isoxazolidine **7b** (33%), and unreacted nitrone **1** (40%), respectively.

Acknowledgment. This research was generously supported by the Naval Sea Systems Command under contract with The Pennsylvania State University, Applied Research Laboratory, and the donors of the Petroleum Research Fund, administered by the American Chemical Society. We also acknowledge the support of Dr. William White and Judy Garland, who have made the facilities of the Materials Research High Pressure Laboratory available to us, Dr. R. Minard for mass spectra, and Alan Freyer for FT NMR spectra. Partial support for the purchase of a Bruker WP-200 from the National Science Foundation is also gratefully acknowledged. Helpful discussions with Joe Perez are also acknowledged.

Registry No. 1, 81206-51-1; (*E*)-**2**, 81206-52-2; (*Z*)-**2**, 81206-53-3; **3**, 109-92-2; **4**, 872-36-6; **5a**, 81206-54-4; **5b**, 81206-55-5; **7a**, 81206-56-6; **7b**, 81244-92-0; **8a**, 81206-57-7; **8b**, 81206-58-8; **9**, 24423-88-9; **10**, 81206-59-9; (*E*)-**11**, 81206-60-2; (*Z*)-**11**, 81206-61-3; **12b**, 81206-62-4; benzaldehyde, 100-52-7; *N*-methylhydroxylamine hydrochloride, 4229-44-1; *N*,*N*-diethylhydroxylamine, 3710-84-7; *N*-hydroxypyrrolidine, 5904-62-1.

Diels–Alder Reactions of (Trifluoromethyl)ethene and (Trifluoromethyl)styrenes with Functionalized Butadienes

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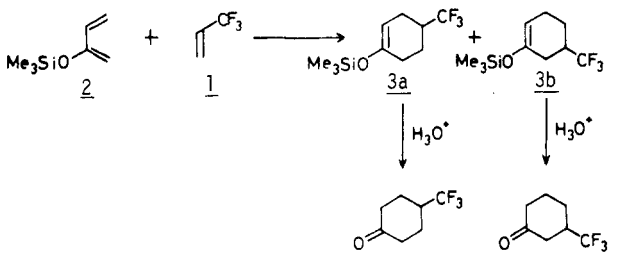
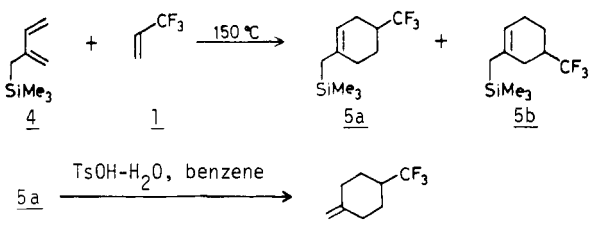
The Diels–Alder reactions of (trifluoromethyl)ethene (**1**) with 2-(trimethylsiloxy)buta-1,3-diene (**2**), 2-[(trimethylsilyl)methyl]-1,3-butadiene (**4**), and 1-methoxy-3-(trimethylsiloxy)buta-1,3-diene (**6**) were carried out to give the corresponding [4 + 2] cycloadducts in 17–38% yields. It was found that the former two cycloadducts were a mixture of para (major) and meta (minor) isomers, while the latter was the para isomer exclusively. Similarly, β-(trifluoromethyl)-4-(methoxycarbonyl)styrene (**9**) and β-(trifluoromethyl)-4-nitrostyrene (**10**) were allowed to react with **4** and **6**, giving the corresponding [4 + 2] cycloadducts in 56–90% yields. The regioselectivity of the reaction on using **6** as the diene turned out to be extremely high, leading to the formation of only one regioisomer. The substituent effect of the trifluoromethyl group in the Diels–Alder reaction in terms of regioselectivity is discussed.

Recently, it has been shown that the introduction of a trifluoromethyl group into a biologically active compound often brings about unique physiological activities.[1] For introduction of the trifluoromethyl group into a carbon skeleton, trifluoromethylation,[2] direct fluorination,[3] and halogen exchange reactions[4] are possible methods. However, such methods are sometimes accompanied by low reactivity and low selectivity. On the other hand, the use of a proper building block which already has the trifluoromethyl group in it is another promising approach. From this point of view, we chose (trifluoromethyl)ethene and (trifluoromethyl)styrenes as fundamental building blocks and dienophiles for Diels–Alder reaction in the present study. Although only one report described the Diels–Alder reaction of (trifluoromethyl)ethene (**1**), the dienes employed in the reaction were restricted to symmetrical dienes, i.e., cyclopentadiene, butadiene, and anthracene.[5] In order to look at the regioselectivity of the

Scheme I



Scheme II



(1) For example: (a) Smith, F. A. CHEMTECH **1973**, 422. Filler, R. *Ibid.* **1974**, 752. (b) Lin, T.-S.; Chai, C.; Prusoff, W. H. *J. Med. Chem.* **1976**, *19*, 915.

(2) For example: (a) Haszeldine, R. N.; Mir, I.-D.; Tipping, A. E.; Wilson, A. G. *J. Chem. Soc., Perkin Trans. 1* **1976**, 1170. (b) McLoughlin, V. C. R.; Thrower, J. *Tetrahedron* **1969**, *25*, 5921. (c) Kobayashi, Y.; Kumadaki, I. *Tetrahedron Lett.* **1969**, 4095.

(3) For example: (a) Tyczkowski, E. A.; Bigelow, L. A. *J. Am. Chem. Soc.* **1955**, *77*, 3007. (b) Attaway, J. A.; Groth, R. H.; Bigelow, L. A. *Ibid.* **1959**, *81*, 3599.

(4) For example: (a) Henne, A. L.; Hinkamp, J. B. *J. Am. Chem. Soc.* **1945**, *67*, 1197. (b) Yagupol'skii, L. M.; Marents, M. S. *Zh. Obshch. Khim.* **1954**, *24*, 887; *Chem. Abstr.* **1955**, *49*, 8172*d*.

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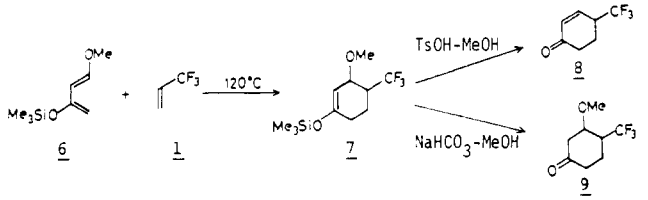
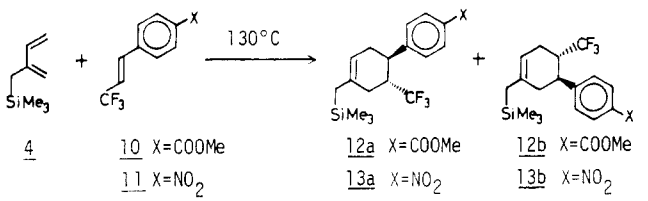
Scheme III



Scheme IV



reaction as well as synthesizing versatile synthetic intermediates, we employed 2-(trimethylsiloxy)buta-1,3-diene (**2**), 2-[(trimethylsilyl)methyl]-1,3-butadiene (**4**), and 1-methoxy-3-(trimethylsiloxy)buta-1,3-diene (**6**) as unsymmetrical dienes.

Results

The Diels–Alder reaction of (trifluoromethyl)ethene (**1**) with 2-(trimethylsiloxy)buta-1,3-diene (**2**) (Scheme I) was carried out at 150 °C for 72 h in a Pyrex ampule to give a mixture of 4-(trifluoromethyl)-1-(trimethylsiloxy)cyclohex-1-ene (**3a**) and 5-(trifluoromethyl)-1-(trimethylsiloxy)cyclohex-1-ene (**3b**) in 17% yield (**3a**/**3b** ratio of 76/24). Each regioisomer (**3a** or **3b**) was isolated by preparative GLC and submitted to hydrolysis to give 4-(trifluoromethyl)cyclohexan-1-one or 3-(trifluorometyl)-cyclohexan-1-one in quantitative yield.

In a similar manner, the reaction of **1** with **4** was carried out (Scheme II) to give a mixture of 4-(trifluoromethyl)-1-[(trimethylsilyl)methyl]cyclohex-1-ene (**5a**) and 5-(trifluoromethyl)-1-[(trimethylsilyl)methyl]cyclohex-1-ene (**5b**) in 38% yield (**5a**/**5b** ratio of 69/31). Protodesilylation of **5a** gave 1-methylidene-4-(trifluoromethyl)cyclohexane in quantitative yield.

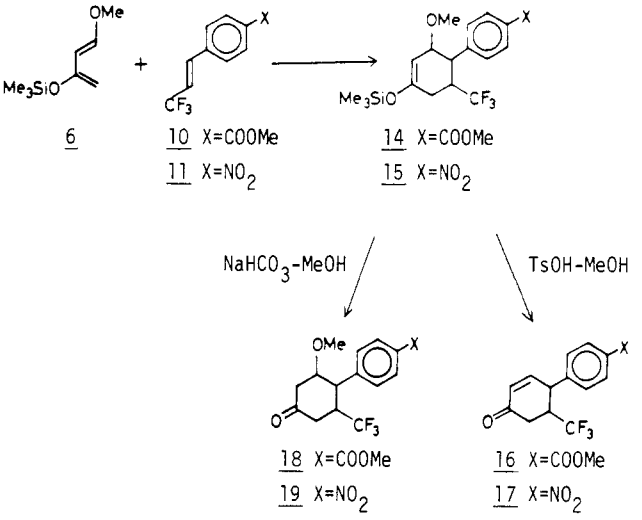
In sharp contrast with the results mentioned above, the Diels–Alder reaction of **1** with 1-methoxy-3-(trimethylsiloxy)butadiene (**6**) proceeded regioselectively (Scheme III) to give 3-methoxy-4-(trifluoromethyl)-1-(trimethylsiloxy)cyclohex-1-ene (**7**) in 25% yield (trans/cis ratio of 75/25). The formation of the other regioisomer was not observed at all. The acid hydrolysis of **7** afforded 4-(trifluoromethyl)cyclohex-2-en-1-one (**8**) in 87% yield, while alkaline hydrolysis gave 3-methoxy-4-(trifluoromethyl)-cyclohexan-1-one (**9**) in 93% yield.

The compounds **7–9** thus obtained may serve as versatile synthetic intermediates for trifluoromethyl-containing polycyclic systems.

As it turned out that (trifluoromethyl)ethene (**1**) had rather low reactivity toward the functionalized dienes **2**, **4**, and **6**, we employed β-(trifluoromethyl)styrenes bearing electron-withdrawing groups on the phenyl ring, i.e., *trans*-β-(trifluoromethyl)-4-(methoxycarbonyl)styrene (**9**) and *trans*-β-(trifluoromethyl)-4-nitrostyrene (**10**). (Trifluoromethyl)styrenes **9** and **10** were readily prepared by palladium-catalyzed arylation of (trifluoromethyl)ethene.[6]

The reaction of **10** or **11** with **4** (Scheme IV) was carried out at 130 °C for 72 h to give a mixture of 4-aryl-5-(trifluoromethyl)-1-[(trimethylsilyl)methyl]cyclohex-1-ene (**12a** or **13a**) and 5-aryl-4-(trifluoromethyl)-1-[(trimethylsilyl)methyl]cyclohex-1-ene (**12b** or **13b**) in good yield (**12a**/**12b** ratio of 57/43, 70%; **13a**/**13b** ratio of 61/39, 85%).[12] Thus, the introduction of an electron-deficient aryl group at C-2 position of **1** increased the reactivity remarkably.

Scheme V



As the Diels–Alder adducts **12** and **13** are allylsilanes, the introduction of alkyl groups, acyl groups, 1-hydroxyalkyl groups, etc. is possible by using S_E2'-type reactions.[7]

The Diels–Alder reaction of **10** or **11** with **6** (Scheme V) gave rise to the formation of only one regioisomer in good yield. Namely, the cycloaddition of **10** with **6** gave 3-methoxy-4-[4-(methoxycarbonyl)phenyl]-5-(trifluoromethyl)-1-(trimethylsiloxy)cyclohex-1-ene (**14**) in 56% yield (cis,trans/trans,trans ratio of 77/23), and the reaction of **11** with **6** gave 3-methoxy-4-(4-nitrophenyl)-5-(trifluoromethyl)-1-(trimethylsiloxy)cyclohex-1-ene (**15**) in 63% yield (cis,trans/trans,trans ratio of 83/17).

Hydrolysis of **14** and **15** by *p*-toluenesulfonic acid–methanol gave 4-aryl-5-(trifluoromethyl)cyclohex-2-en-1-ones **16** and **17** in 90% and 91% yields, respectively, while desilylation of **14** and **15** by $NaHCO_3$–methanol gave 4-aryl-3-methoxy-5-(trifluoromethyl)cyclohexan-1-ones **18** and **19** in 89% and 97% yields, respectively.

The compounds **14–19** thus obtained may serve as useful synthetic intermediates for the construction of polycyclic systems involving an aromatic ring, and they may be used as precursors for biphenyls bearing a trifluoromethyl group.

Discussion

According to Houk's calculation,[8] the preferred Diels–Alder regioisomer can be predicted by the generalizations that (i) "the principal stabilization of the transition state will arise from interaction of the HO–LU pair of addend frontier orbitals which are closest in energy" and that (ii) "the larger terminal coefficient on each addend will become bonded preferentially in the transition state". For example, the Diels–Alder reaction of a butadiene having an electron-releasing substituent at C-2 with an ethene having an electron-withdrawing group should proceed via the interaction of the HOMO of the diene and LUMO of the ethene to give the para isomer as a preferential cyclo-

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(6) Fuchikami, T.; Yatabe, M.; Ojima, I. *Synthesis* **1981**, 365.
(7) For a review, see: Chan, T. H.; Fleming I. *Synthesis* **1979**, 761 and references cited therein.
(8) Houk, K. N. *J. Am. Chem. Soc.* **1973**, *95*, 4092.

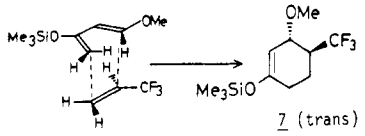


Figure 1.

adduct. As described above, the Diels–Alder reaction of (trifluoromethyl)ethene (1) with 2-(trimethylsiloxy)butadiene (2) or 2-[(trimethylsilyl)methyl]-1,3-butadiene (4) afforded the para isomer as the major product although the observed regioselectivity was only moderate. This fact may imply that trifluoromethyl is a strong electron-withdrawing group which interacts with the LUMO of ethene, inductively lowering the LUMO, and this purely inductive effect also increases the relative magnitude of the coefficient of the unsubstituted terminus, but the effect is not sufficient to achieve high reactivity and high regioselectivity toward dienes 2 and 4. In the case of 1-methoxy-3-(trimethylsiloxy)butadiene (6), however, the exclusive formation of the para isomer with regard to trifluoromethyl and trimethylsiloxy groups was observed. The result strongly suggests that the introduction of 1-methoxy and 3-trimethylsiloxy groups to butadiene gives rise to the remarkable increase both in the HOMO level, which strengthenes the interaction with LUMO of 1, and in the coefficient of C-4. These effects bring about the complete regioselectivity. In other words, the diene 6 can recognize the difference in the coefficients of two termini in 1 quite effectively. Rather low chemical yields in the reactions of 1 are ascribed to the polymerization of dienes 2, 4, and 6 under the reaction conditions employed.

Introduction of the 4-substituted phenyl group at the C-2 terminus of 1 is interesting not only because it increases the reactivity of the dienophile, i.e., decrease in LUMO level, but also because it may allow us to estimate the relative magnitude of the effect of trifluoromethyl group on regioselectivity. Although we anticipated that the trifluoromethyl might control the regioselectivity since the trifluoromethyl is inductively more electron-withdrawing than 4-(methoxycarbonyl)phenyl or 4-nitrophenyl, the results with 4 and 6 as dienes and 10 and 11 as dienophiles clearly indicate that the aryl groups have a greater influence on the rate and regioselectivity than the trifluoromethyl group in the Diels–Alder reaction; viz., the results are contrary to what is predicted on the basis of purely inductive effects.

It also turns out that the diene 6 can distinguish the difference in the coefficients of two termini in 10 or 11 in an extremely effective manner to give only one regioisomer. On the other hand, the stereoselectivities observed in the reactions of 6 with 1, 10, or 11 were only moderate: 7 (trans/cis ratio of 75/25), 14 (cis,trans/trans,trans ratio of 77/23), 15 (cis,trans/trans,trans ratio of 83/17). The results imply that the trifluoromethyl simply acts as an inductively electron-withdrawing substituent, and it does not have any secondary orbital interactions with the dienes. The favorable transition state for the reaction of 6 with 1 is depicted in Figure 1, and that for the reaction of 6 with 10 or 11 is shown in Figure 2. In the latter case, the secondary orbital effects of the aryl groups, i.e., the aryl–endo interactions, are taken into account and favor the formation of cis,trans isomers.

Experimental Section

Measurements. Boiling points and melting points were uncorrected. ^{1}H NMR spectra were recorded on Varian EM-360, EM-390, or XL-100-15A spectrometers with tetramethylsilane as the internal standard. ^{19}F NMR spectra were measured with

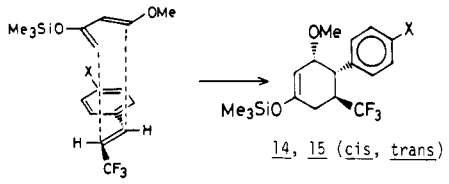


Figure 2.

Hitachi R-20B or Varian XL-100-15A spectrometers with fluorotrichloromethane as the internal standard or trifluoroacetic acid as the external standard. Chemical shifts (δ) in parts per million from the internal standard are given as positive values for downfield shifts in all cases. Infrared spectra were recorded on a JASCO A-202 spectrophotometer by using samples as neat liquids or KBr disks. Mass spectra were measured with a Hitachi RMU-6MG spectrometer at 70 eV. Analytical GLC was carried out with a Shimadzu GC-7A using columns packed with 30% DC-550, 30% SE-30, or 20% PEG-6000 on Uniport B. Preparative GLC was performed with a Varian Aerograph Model 920 using columns packed with 30% SE-30 or 20% PEG-6000 on Uniport B.

Materials. (Trifluoromethyl)ethene (1) was commercially available and used as purchased. β-(Trifluoromethyl)-4-(methoxycarbonyl)styrene (10) and β-(trifluoromethyl)-4-(nitrophenyl)styrene (11) were prepared by reacting 4-(methoxycarbonyl)iodobenzene and 4-nitroiodobenzene with 1, respectively, in the presence of palladium acetate in triethylamine.[6] 2-(Trimethylsiloxy)buta-1,3-diene (2) was prepared by the trimethylsilylation of methyl vinyl ketone.[9] 2-[(Trimethylsilyl)-methyl]-1,3-butadiene (4) was prepared by the reaction of (trimethylsilyl)methyl Grignard reagent with chloroprene in the presence of $NiCl_2$(dppp) [dppp = bis(diphenylphosphino)-propane].[10] 1-Methoxy-3-(trimethylsiloxy)buta-1,3-diene (6) was prepared by the trimethylsilylation of 4-methoxybut-3-en-2-one.[11]

Reaction of (Trifluoromethyl)ethene (1) with 2-(Trimethylsiloxy)buta-1,3-diene (2). In a Pyrex tube 1 (2.0 mL at −78 °C) was added to degassed 2 (534 mg, 3.76 mmol), and the tube was sealed. Then, the mixture was heated at 150 °C for 72 h. The tube was cooled to −78 °C and opened. Distillation of the reaction mixture under reduced pressure gave 150 mg (17% yield) of 3. The product ratio **3a**/**3b** was determined to be 76/24 based on GLC analysis. The cycloadducts **3a** and **3b** were isolated by preparative GLC.

3a: ^{1}H NMR ($CDCl_3$) δ 0.17 (s, 9 H), 1.57 (m, 7 H), 4.83 (m, 1 H); ^{19}F NMR ($CDCl_3$, CF_3COOH) δ 5.35 (d, J = 7.5 Hz); mass spectrum, m/e 238 (M^+).

3b: ^{1}H NMR ($CDCl_3$) δ 0.17 (s, 9 H), 1.5–2.7 (m, 7 H), 5.14 (m, 1 H); ^{19}F NMR ($CDCl_3$, CF_3COOH) δ 5.07 (d, J = 8 Hz); mass spectrum, m/e 238 (M^+).

A mixture of **3a** and **3b** (180 mg) obtained from another run was submitted to hydrolysis by using 0.1 N hydrochloric acid (10 mL) to obtain further supports for the structure of cycloadducts, which gave the corresponding 3-(trifluoromethyl)- and 4-(trifluoromethyl)cyclohexan-1-ones in almost quantitative yield (GLC analysis). Each regioisomer was isolated by preparative GLC.

4-(Trifluoromethyl)cyclohexan-1-one: ^{1}H NMR ($CDCl_3$) δ 1.58–2.68 (m); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −73.53 (d, J = 8 Hz); IR (neat) 1720 ($\nu_{C=O}$) cm^{-1}; mass spectrum, m/e 166 (M^+). Anal. Calcd for $C_7H_9F_3O$: C, 50.61; H, 5.46. Found: C, 50.56; H, 5.43.

3-(Trifluoromethyl)cyclohexan-1-one: ^{1}H NMR ($CDCl_3$) δ 1.55–2.70 (m); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −74.43 (d, J = 7 Hz); IR (neat) 1720 ($\nu_{C=O}$) cm^{-1}; mass spectrum, m/e 166 (M^+). Anal. Calcd for $C_7H_9F_3O$: C, 50.61; H, 5.46. Found: C, 50.45; H, 5.48.

Reaction of (Trifluoromethyl)ethene (1) with 2-[(Trimethylsilyl)methyl]-1,3-butadiene (4). Geseous 1 (2.24 L, 100

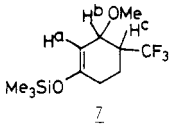
(9) Jung, M. E.; McCombs, C. A. *Tetrahedron Lett.* **1976**, 2935.
(10) Hosomi, A.; Saito, M.; Sakurai, H. *Tetrahedron Lett.* **1979**, 429. As for the Diels–Alder reactions of 2-[(trimethylsilyl)methyl]-1,3-butadine, see: Hosomi, A.; Saito, M.; Sasaki, J.; Iguchi, H.; Sakurai, H. Abstracts of the 27th Symposium on Organometallic Chemistry Japan, Osaka, Oct 14–15, 1980; p B106.
(11) Danishefsky, S.; Kitahara, T. *J. Am. Chem. Soc.* **1974**, *96*, 7807.
(12) Structural assignment of two regioisomers was made on the basis of the regioselectivity observed for the formation of 14 or 15.

mmol) was introduced to the mixture of **4** (1.44 g, 10.3 mmol) and hydroquinone (20 mg) in a 50-mL stainless-steel autoclave cooled with liquid N_2. The mixture was heated at 150 °C for 90 h. Then, the reaction mixture was cooled to 0 °C, and the excess **1** was removed. The product ratio and the yield were determined on the basis of ^{19}F NMR with benzotrifluroide as the internal standard: **5a**/**5b** ratio of 69/31; 38% yield. The cycloadducts **5a** and **5b** were isolated by preparative GLC.

5a: ^1H NMR ($CDCl_3$) δ −0.02 (s, 9 H), 1.42 (s, 2 H), 1.32–2.38 (m, 7 H), 5.17 (br s, 1 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −74.21 (d, J = 8 Hz); IR (neat) 1670 ($\nu_{C=C}$) cm^{-1}; mass spectrum, m/e 236 (M^+).

5b: ^1H NMR ($CDCl_3$) δ −0.02 (s, 9 H), 1.42 (s, 2 H), 1.34–2.24 (m, 7 H), 5.22 (br s, 1 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −74.39 (d, J = 8 Hz); IR (neat) 1670 ($\nu_{C=C}$) cm^{-1}; mass spectrum, m/e 236 (M^+). Anal. Calcd for $C_{11}H_{19}F_3Si$: C, 55.90; H, 8.10. Found: C, 56.30; H, 8.12 (for a mixture of **5a** and **5b**).

Reaction of (Trifluoromethyl)ethene (1) with 1-Methoxy-3-(trimethylsiloxy)buta-1,3-diene (6). Gaseous **1** (2.98 L, 133 mmol) was introduced to the mixture of **6** (6.88 g, 40 mmol) and hydroquinone (11 mg) in a 50-mL stainless-steel autoclave cooled with liquid N_2, and the mixture was heated at 120 °C for 163 h. After the mixture was cooled to 0 °C and excess **1** removed, the reaction mixture was submitted to ^{19}F NMR analysis for the determination of the cis/trans ratio by using benzotrifluoride as the internal standard: *trans*-**7**/*cis*-**7** ratio of 75/25. Distillation of the reaction mixture under reduced pressure gave 2.97 g (28% yield) of cycloadduct **7**, bp 106–107 °C (22 mmHg). The cycloadducts *trans*-**7** and *cis*-**7** were isolated by preparative GLC.



7

trans-**7**: $^1H\{^{19}F\}$ NMR ($CDCl_3$) δ 0.18 (s, 9 H), 1.60–2.60 (m, 5 H), 3.31 (s, 3 H), 4.06 (dd, $J_{H^a-H^b}$ = 3.6 Hz, $J_{H^b-H^c}$ = 6 Hz, 1 H), 4.96 (d, $J_{H^a-H^b}$ = 3.6 Hz, 1 H) (coupling constants were determined by using the decoupling technique); ^{19}F NMR ($CDCl_3$, CF_3COOH) δ 9.18 (d, J = 9 Hz); IR (neat) 1670 ($\nu_{C=C}$) cm^{-1}; mass spectrum, m/e 268 (M^+).

cis-**7**: $^1H\{^{19}F\}$ NMR ($CDCl_3$) δ 0.20 (s, 9 H), 1.7–2.4 (m, 5 H), 3.33 (s, 3 H), 4.00 (dd, $J_{H^a-H^b}$ = 5.5 Hz, $J_{H^b-H^c}$ = 2 Hz, 1 H), 5.15 (d, $J_{H^a-H^b}$ = 5.5 Hz, 1 H) (coupling constants were determined by using the decoupling technique); ^{19}F NMR ($CDCl_3$, CF_3COOH) δ 10.06 (d, J = 8 Hz); IR (neat) 1665 ($\nu_{C=C}$) cm^{-1}; mass spectrum, m/e 268 (M^+). Anal. Calcd for $C_{11}H_{19}F_3O_2Si$: C, 49.23, H, 7.14. Found: C, 49.53; H, 7.11 (for a mixture of *trans*-**7** and *cis*-**7**).

A mixture of *trans*-**7** and *cis*-**7** was submitted to desilylation in two ways. First, **7** (1.34 g, 5 mmol) was dissolved in methanol (10 mL) containing 70 mg of *p*-toluenesulfonic acid (TsOH) and stirred at 20 °C for 10 min. ^{19}F NMR analysis with benzotrifluoride as the internal standard revealed that **8** was formed in 87% yield. Then, the solvent was removed, and the residue was distilled under reduced pressure to give 508 mg (71%) of **8**, bp 75–77 °C (22 mmHg). Second, **7** (500 mg) was dissolved in methanol (20 mL), and sodium bicarbonate (30 mg) was added to the solution. Then, the mixture was heated at 50 °C for 3 h with stirring. ^{19}F NMR analysis with benzotrifluoride as the internal standard showed that **9** was formed in 93% yield. After the usual workup, the residue was submitted to preparative GLC separation to give *trans*-**9** and *cis*-**9**.

8: ^1H NMR ($CDCl_3$) δ 1.90–2.90 (m, 4 H), 3.19 (m, 1 H), 6.13 (dd, J = 10.5, 2.5 Hz, 1 H), 6.88 (m, 1 H); ^{19}F NMR ($CDCl_3$, CF_3COOH) δ 6.77 (d, J = 9.5 Hz); IR (neat) 1695 ($\nu_{C=O}$), 1630 ($\nu_{C=C}$) cm^{-1}; mass spectrum, m/e 164 (M^+). Anal. Calcd for $C_7H_7F_3O$: C, 51.23; H, 4.30. Found: C, 51.26; H, 4.36.

trans-**9**: ^1H NMR ($CDCl_3$) δ 1.62–2.80 (m, 7 H), 3.30 (s, 3 H), 3.81 (dd, J = 9, 5 Hz, 1 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −69.98 (d, J = 7 Hz); IR (neat) 1720 ($\nu_{C=O}$) cm^{-1}; mass spectrum, m/e 196 (M^+). Anal. Calcd for $C_8H_{11}F_3O_2$: C, 48.98; H, 5.65. Found: C, 49.00; H, 5.85.

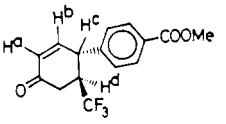
cis-**9**: ^1H NMR ($CDCl_3$) δ 1.87–2.89 (m, 7 H), 3.29 (s, 3 H), 4.03 (m, 1 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −69.45 (d, J = 7 Hz); IR (neat) 1720 ($\nu_{C=O}$) cm^{-1}; mass spectrum, m/e 196 (M^+). Anal. Calcd for $C_8H_{11}F_3O_2$: C, 48.98; H, 5.65. Found: C, 48.69; H, 5.77.

Reaction of β-(Trifluoromethyl)-4-(methoxycarbonyl)styrene (10) with 4. A mixture of **10** (500 mg, 2.17 mmol), **4** (870 mg, 6.21 mmol), and hydroquinone (5 mg) was sealed in a Pyrex tube and heated at 130 °C for 45 h. The reaction mixture was submitted to column chromatography on silica gel with benzene–hexane (1:2) as the eluent to give **12**, 620 mg (77% yield).

The product, **12**, turned out to be a mixture of two regioisomers, **12a** and **12b**, by ^1H and ^{19}F NMR analysis: **12a**/**12b** ratio of 57/43; ^1H NMR ($CDCl_3$) δ 0.01 (s, **a**), 0.05 (s, **b**) (9 H), 1.31 (s, **b**), 1.35 (s, **a**) (2 H), 1.81–3.05 (m, 6 H), 3.51 (s, **b**), 3.55 (s, **a**) (3 H), 5.15 (br s, 1 H), 6.80 (d, J = 9 Hz, **b**), 6.97 (d, J = 8 Hz, **a**) (2 H), 8.00 (d, J = 9 Hz, **b**), 8.15 (d, J = 8 Hz, **a**) (2 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −69.25 (d, J = 8 Hz, **a**), −69.00 (d, J = 8 Hz, **b**); IR (neat) 1730 ($\nu_{C=O}$), 1670 ($\nu_{C=C}$) cm^{-1}; mass spectrum, m/e 370 (M^+). Anal. Calcd for $C_{19}H_{25}F_3O_2Si$: C, 61.60; H, 6.80. Found: C, 61.59; H, 6.58.

Reaction of β-(Trifluoromethyl)-4-nitrostyrene (11) with 4. In a manner similar to that of the reaction of **10** with **4**, a mixture of **11** (450 mg, 2.07 mmol), **4** (870 mg, 6.21 mmol), and hydroquinone (5 mg) was heated in a Pyrex tube at 130 °C for 59 h, and the cycloadduct **13** was obtained by a column chromatography on silica gel (eluent benzene–hexane, 1:1) in 90% yield (670 mg). The ratio of **13a**/**13b** was 61/39 (by ^{19}F NMR). **13a,b**: ^1H NMR ($CDCl_3$) δ −0.02 (s, **b**), 0.01 (s, **a**) (9 H), 1.48 (br s, 2 H), 2.10–3.15 (m, 6 H), 5.31 (br s, 1 H), 7.34 (d, J = 10 Hz, 2 H), 8.11 (d, J = 10 Hz, 2 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −69.15 (d, J = 8 Hz, **a**), −68.82 (d, J = 8 Hz, **b**); IR (neat) 1670 ($\nu_{C=C}$) cm^{-1}; mass spectrum, m/e 357 (M^+). Anal. Calcd for $C_{17}H_{22}F_3NO_2Si$: C, 57.12; H, 6.20; N, 3.92. Found: C, 57.01; H, 6.32; N, 3.86.

Reaction of β-(Trifluoromethyl)-4-(methoxycarbonyl)styrene (10) with 1-Methoxy-3-(trimethylsiloxy)buta-1,3-diene (6). A mixture of **10** (475 mg, 2.07 mmol), **6** (1.72 g, 10.0 mmol), and hydroquinone (13 mg) was sealed in a Pyrex tube and heated at 150 °C for 40 h. ^{19}F NMR analysis of the reaciton mixture with benzotrifluoride as the internal standard showed that **14** was produced in 56% yield (*cis,trans*-**14**/*trans,trans*-**14** ratio of 77/23). The reaction mixture was submitted to methanolysis in a manner similar to the desilylation of **7**. First, half of the reaction mixture was treated with MeOH–TsOH at 0 °C for 2 h. ^{19}F NMR analysis (standard $C_6H_5CF_3$) revealed that **16** was formed in 90% yield. Compound **16** was isolated by column



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chromatography on silica gel (eluent $CHCl_3$). Second, the other half of the reaction mixture was desilylated with MeOH–$NaHCO_3$ at 50 °C for 3 h. ^{19}F NMR analysis showed that **18** was formed in 97% yield (*cis,trans*-**18**/*trans,trans*-**18** ratio of 77/23). Both *cis,trans*-**18** and *trans,trans*-**18** were isolated by a column chromatography on silica gel (eluent *n*-hexane–$CHCl_3$).

16: ^1H NMR ($CDCl_3$) δ 1.10–1.72 (m, 2 H), 2.54–3.20 (m, 2 H), 3.91 (s, 3 H), 6.26 (dd, $J_{H^a-H^b}$ = 10 Hz, $J_{H^a-H^c}$ = 2 Hz, 1 H), 6.74 (dd, $J_{H^a-H^b}$ = 10 Hz, $J_{H^b-H^c}$ = 3 Hz, 1 H), 8.30 (d, J = 8 Hz, 2 H), 9.05 (d, J = 8 Hz, 2 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −70.54 (d, J = 8 Hz); IR (neat) 1730 ($\nu_{C=O}$), 1690 ($\nu_{C=O}$), 1610 ($\nu_{C=C}$) cm^{-1}; mass spectrum, m/e 298 (M^+). Anal. Calcd for $C_{15}H_{13}F_3O_3$: C, 60.41; H, 4.39. Found: C, 60.12; H, 4.60.

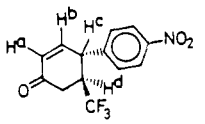
cis,trans-**18**: ^1H NMR ($CDCl_3$) δ 2.44–3.60 (m, 6 H), 3.74 (m, 1 H), 3.22 (s, 3 H), 3.92 (s, 3 H), 7.51 (d, J = 8 Hz, 2 H), 8.03 (d, J = 8 Hz, 2 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −70.16 (d, J = 8 Hz); IR (neat) 1725 ($\nu_{C=O}$) cm^{-1}; mass spectrum, m/e 330 (M^+). Anal. Calcd for $C_{16}H_{17}F_3O_4$: C, 58.18; H, 5.19. Found: C, 58.27; H, 5.11.

trans,trans-**18**: ^1H NMR ($CDCl_3$) δ 2.34–3.60 (m, 6 H), 3.22 (s, 3 H), 3.64 (ddd, J = 9, 8, 4 Hz, 1 H), 3.94 (s, 3 H), 7.36 (d, J = 8 Hz, 2 H), 8.08 (d, J = 8 Hz, 2 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −69.90 (d, J = 8 Hz); IR (neat) 1730 ($\nu_{C=O}$) cm^{-1}; mass spectrum, m/e 330 (M^+). Anal. Calcd for $C_{16}H_{17}F_3O_4$: C, 58.18; H, 5.19. Found: C, 58.39; H, 5.39.

Reaction of β-(Trifluoromethyl)-4-nitrostyrene (11) with 1-Methoxy-3-(trimethylsiloxy)buta-1,3-diene (6). A mixture of **11** (437 mg, 2.10 mmol), **6** (1.73 g, 10.0 mmol), and hydroquinone (20 mg) was sealed in a Pyrex tube and heated at 130 °C for 65

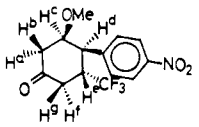
h. ^{19}F NMR analysis (standard $C_6H_5CF_3$) showed that cycloadduct **15** was formed in 63% yield (*cis,trans*-**15**/*trans,trans*-**15** ratio of 83/17). The reaction mixture was submitted to methanolysis in a manner similar to that for the desilylation of **14**.

Treatment of the reaction mixture with MeOH–TsOH at 0 °C for 2 h gave **17** in 89% yield (^{19}F NMR analysis). Compound **17**

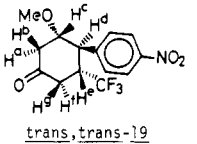


17

was isolated by a column chromatography on silica gel (eluent $CHCl_3$); mp 82–83 °C (from benzene–hexane). Desilylation by treating with MeOH–$NaHCO_3$ at 50 °C for 3 h afforded **19** in 91% yield (^{19}F NMR analysis; *cis,trans*-**19**/*trans,trans*-**19** ratio of 83/17). Both *cis,trans*-**19** and *trans,trans*-**19** were isolated by



cis,trans-**19**



trans,trans-**19**

a column chromatography on silica gel (eluent $CHCl_3$): *cis,trans*-**19**, mp 127–131 °C; *trans,trans*-**19**, mp 117.5–118.5 °C.

17: $^1H\{^{19}F\}$ NMR ($CDCl_3$) δ 2.48–3.26 (m, 3 H), 4.08 (d of t, $J_{H^a-H^c} = J_{H^b-H^c} = 2.5$ Hz, $J_{H^c-H^d} = 8$ Hz, 1 H), 6.30 (dd, $J_{H^a-H^b} = 10$ Hz, $J_{H^b-H^c} = 2.5$ Hz, 1 H), 6.76 (dd, $J_{H^a-H^b} = 10$ Hz, $J_{H^a-H^c} = 2.5$ Hz, 1 H), 7.46 (d, $J = 8$ Hz, 2 H), 8.28 (d, $J = 8$ Hz, 2 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −70.35 (d, $J = 7.5$ Hz); IR (KBr) 1690 ($\nu_{C=O}$), 1600 ($\nu_{C=C}$) cm^{-1}; mass spectrum, *m/e* 285 (M^+). Anal. Calcd for $C_{13}H_{10}F_3O_3N$: C, 54.74; H, 3.53; N, 4.91. Found: C, 54.78; H, 3.63; N, 4.88.

cis,trans-**19**: $^1H\{^{19}F\}$ NMR ($CDCl_3$) δ 2.46 (dd, $J_{H^f-H^g} = 15$ Hz, $J_{H^e-H^f} = 10.5$ Hz, 1 H), 2.53 (dd, $J_{H^a-H^b} = 15$ Hz, $J_{H^a-H^c} = 2.5$ Hz, 1 H), 2.82 (ddd, $J_{H^f-H^g} = 15$ Hz, $J_{H^g-H^e} = 5$ Hz, $J_{H^g-H^b} = 1.8$ Hz, 1 H), 2.96 (ddd, $J_{H^a-H^b} = 15$ Hz, $J_{H^b-H^c} = 3.6$ Hz, $J_{H^b-H^g} = 1.8$ Hz, 1 H), 3.26 (dd, $J_{H^d-H^e} = 11$ Hz, $J_{H^d-H^c} = 1.5$ Hz, 1 H), 3.45 (ddd, $J_{H^e-H^f} = 10.5$ Hz, $J_{H^e-H^g} = 5$ Hz, $J_{H^e-H^d} = 11$ Hz, 1 H), 3.73 (ddd, $J_{H^c-H^a} = 2.5$ Hz, $J_{H^c-H^b} = 3.6$ Hz, $J_{H^c-H^d} = 1.5$ Hz, 1 H), 7.59 (d, $J = 8$ Hz, 2 H), 8.18 (d, $J = 8$ Hz, 2 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −70.2 (d, $J = 7.5$ Hz); IR (KBr) 1720 ($\nu_{C=O}$) cm^{-1}; mass spectrum, *m/e* 231 (M^+). Anal. Calcd for $C_{14}H_{14}F_3O_4N$: C, 53.00; H, 4.45; N, 4.41. Found: C, 52.94; H, 4.37; N, 4.43.

trans,trans-**19**: $^1H\{^{19}F\}$ NMR ($CDCl_3$) δ 2.50 (dd, $J_{H^a-H^b} = 14$ Hz, $J_{H^a-H^c} = 9.5$ Hz, 1 H), 2.55 (dd, $J_{H^f-H^g} = 14$ Hz, $J_{H^f-H^e} = 12$ Hz, 1 H), 2.75 (ddd, $J_{H^g-H^f} = 14$ Hz, $J_{H^g-H^e} = 4.5$ Hz, $J_{H^g-H^b} = 1.2$ Hz, 1 H), 2.83 (ddd, $J_{H^e-H^d} = 10$ Hz, $J_{H^e-H^f} = 12$ Hz, $J_{H^e-H^g} = 4.5$ Hz, 1 H), 2.95 (ddd, $J_{H^b-H^a} = 14$ Hz, $J_{H^b-H^c} = 4$ Hz, $J_{H^b-H^g} = 1.2$ Hz, 1 H), 3.12 (s, 3 H), 3.22 (dd, $J_{H^d-H^c} = 9$ Hz, $J_{H^d-H^e} = 10$ Hz, 1 H), 3.58 (ddd, $J_{H^c-H^a} = 9.5$ Hz, $J_{H^c-H^b} = 4$ Hz, $J_{H^c-H^d} = 9$ Hz, 1 H), 7.38 (d, $J = 9$ Hz, 2 H), 8.20 (d, $J = 9$ Hz, 2 H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ −69.5 (d, $J = 7$ Hz); IR (KBr) 1730 ($\nu_{C=O}$) cm^{-1}; mass spectrum, *m/e* 231 (M^+). Anal. Calcd for $C_{14}H_{14}F_3O_4N$: C, 53.00; H, 4.45; N, 4.41. Found: C, 53.05; H, 4.46; N, 4.36.

Registry No. 1, 677-21-4; **2**, 38053-91-7; **3a**, 81206-63-5; **3b**, 81206-64-6; **4**, 70901-64-3; **5a**, 81206-65-7; **5b**, 81206-66-8; **6**, 59414-23-2; *trans*-**7**, 81206-67-9; *cis*-**7**, 81206-68-0; **8**, 81206-69-1; *trans*-**9**, 81206-70-4; *cis*-**9**, 81206-71-5; **10**, 78622-58-9; **11**, 78622-57-8; **12a**, 81206-72-6; **12b**, 81206-73-7; **13a**, 81206-74-8; **13b**, 81206-75-9; *cis,trans*-**14**, 81206-76-0; *trans,trans*-**14**, 81244-93-1; *cis,trans*-**15**, 81206-77-1; *trans,trans*-15, 81244-94-2; **16**, 81206-78-2; **17**, 81206-79-3; *cis,trans*-**18**, 81206-80-6; *trans,trans*-18, 81244-95-3; *cis,trans*-**19**, 81206-81-7; *trans,trans*-**19**, 81244-96-4; 1-methylidene-4-(trifluoromethyl)cyclohexane, 81206-82-8; 4-(methoxycarbonyl)iodobenzene, 619-44-3; 4-nitro iodobenzene, 636-98-6; 4-(trifluoromethyl)cyclohexan-1-one, 75091-99-5; 3-(trifluoromethyl)cyclohexan-1-one, 585-36-4.

Rate and Equilibrium Constants for the Reaction of Thiolate Ions with Dibenzo[*c,e*]-1,2-dithiin and Naphtho[1,8-*cd*]-1,2-dithiole 1,1-Dioxides

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In aqueous dioxane the cyclic thiosulfonate dibenzo[*c,e*]-1,2-dithiin 1,1-dioxide (**1**) reacts rapidly with thiolate ions and undergoes opening of the thiosulfonate ring (eq 2), forming disulfide **3a**. Acidification of solutions of **3a** with carboxylic acid buffers of appropriate pH leads to facile reversal of the ring-opening reaction and the quantitative regeneration of **1**. Since this reversal of ring opening is not acid-catalyzed, it must take place via a simple intramolecular displacement of RS^- by the sulfinate (SO_2^-) group present in **3a** and is therefore the microscopic reverse of the ring-opening reaction. Rate constants have been determined for both ring opening (k_{RS}) and reversal of ring opening (k_{-RS}) for a series of alkanethiolates of varying pK_a. From these data one may also calculate the equilibrium constant, K_{eq} (= k_{RS}/k_{-RS}), for reaction of each thiolate with **1**. From comparison of the log K_{eq}'s with previously determined equilibrium constants for reaction of cyanide and sulfite ions with **1** one obtains quantitative information on the thermodynamics of reactions of the type ArSSR + $CN^- \rightleftharpoons$ ArSCN + RS^- and ArSSR + $SO_3^{2-} \rightleftharpoons ArSSO_3^- + RS^-$ that should be of considerable value for predicting the magnitude of equilibrium constants for cyanide–disulfide and sulfite–disulfide equilibria. Plots of log K_{eq}, log k_{RS}, and log k_{-RS} vs. the pK_a of RSH reveal that $\beta_{eq} = 1.25$, $\beta_{RS} = 0.26$, and $\beta_{-RS} = -0.99$. These β values show that the transition state for eq 2 is quite unsymmetrical, with a structure [$RS^{\Delta-}$···S–$SO_2^{\delta-}$] where the RS–S bond is only ~20% formed. The β_{RS} and β_{-RS} values are compared with the β values for several other previously studied displacements involving disulfides. The reaction of naphtho[1,8-*cd*]-1,2-dithiole 1,1-dioxide (**2**) with thiolates behaves in a fashion analogous to that of the reaction of RS^- with **1**. Comparison of K_{eq}, k_{RS}, and k_{-RS} for an equilibrium involving **2** and a thiolate with those for the corresponding thiolate reacting with **1** allows one to assess how a change from a six- to a five-membered thiosulfonate ring influences K_{eq}, k_{RS}, and k_{-RS}. The major effects are that k_{-RS} is much larger and K_{eq} is considerably smaller.

Chau and Kice[1] have shown that the cyclic thiosulfonates **1** and **2**, like ordinary open-chain aryl thiosulfonates, are cleaved readily by excess cyanide or sulfite ion (as shown for **1** in eq 1, step k_{Nu}). However, in dramatic contrast to the behavior of open-chain thiosulfonates, upon acidification of the final reaction solution with buffers sufficiently acidic to protonate CN^- or SO_3^{2-}, the reaction can be reversed (step k_{-Nu}) and the cyclic thiosulfonate rapidly and quantitatively regenerated. The reason that

(1) Chau, M. M.; Kice, J. L. *J. Org. Chem.* **1978**, *43*, 914.

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