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π-Face-Selective Diels−Alder Reactions of 3,4-Di-*tert*-butylthiophene 1-Oxide and 1-Imide and Formation of 1,2-Thiazetidines

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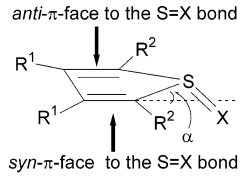
Abstract: 3,4-Di-*tert*-butylthiophene 1-oxide (**1a**) reacted with a series of electron-deficient alkenic dienophiles at its *syn*-π-face relating to the S═O bond to give [4+2] adducts in excellent yields. The 1-oxide **1a** also reacted even with angle-strained dienophiles acenaphthylene and norbornene at its *syn*-π-face to afford [4+2] adducts; in the latter case, norbornene reacted exclusively at its *exo*-π-face. The oxide **1a** reacted with dimethyl acetylenedicarboxylate to produce dimethyl 4,5-di-*tert*-butylphthalate in high yield with spontaneous extrusion of SO from the initial adduct even at room temperature. Similarly, 3,4-di-*tert*-butylthiophene 1-(*p*-toluenesulfonyl)imide (**3a**) reacted with alkenic dienophiles at its *syn*-π-face relating to the S═N bond to give [4+2] adducts in good yields. The reaction of **3a** with 4-phenyl-1,2,4-triazoline-3,5-dione (PTAD) afforded a 1,2-thiazetidine **12a**, the first example of S-unoxidized 1,2-thiazetidine, in good yield, through rearrangement of the initial [4+2] adduct. The molecular structure of **12a** is discussed on the basis of the X-ray crystallographic analysis. Comparison of the foregoing reactions leads to the conclusion that the 1-oxide **1a** is more reactive as a diene than the 1-imide **3a**, which is more reactive than 3,4-di-*tert*-butylthiophene 1,1-dioxide. The origin of the *syn*-π-face selectivities of **1a** and **3a** in Diels−Alder reactions is discussed in terms of the orbital mixing rule and steric effect and also based on B3LYP/6-31G(d) calculations.

Introduction

S-Oxidized thiophenes, thiophene 1-oxides (**1**) and thiophene 1,1-dioxides (**2**), which are no longer aromatic, are highly reactive species and thus behave both as a cyclic diene and as a dienophile. They undergo a rapid [2+4]-self-dimerization if they are neither protected sterically nor stabilized electronically. They also serve as Michael acceptors as an unsaturated cyclic sulfoxide or sulfone. The chemistry of **2** has been studied extensively[1] including that of the parent compound,[2] whereas the chemistry of **1** has recently become a matter of keen interest from viewpoints of synthesis, reactivities, and intermediates of metabolism of thiophenes.[3,4] X-ray crystallographic analyses have revealed that monocyclic **1** has the general structure shown in Figure 1 (X = O).[5] Accordingly, they possess two π-faces, *syn* and *anti* relating to the S═O bond, when they act as a diene for Diels−Alder reactions. A few recent reports have revealed that 2,5-disubstituted **1** undergoes a π-face-selective Diels−Alder reaction in an *endo*-mode, whereby dienophiles add to **1** from the *syn*-direction relating to the S═O bond.[5d,6]



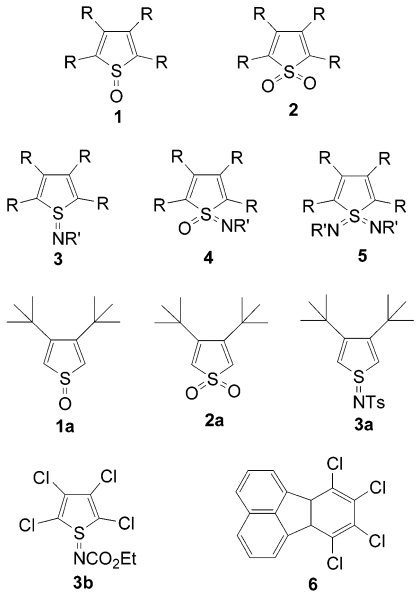
1a: R^1 = *tert*-Bu, R^2 = H, X = O; α = 9.3°
3a: R^1 = *tert*-Bu, R^2 = H, X = NTs; α = 11.1°

Figure 1.

Substitution of oxygen atom(s) of **1** and **2** by nitrogen substituent(s) leads to nitrogen analogues **3**, **4**, and **5**, whose chemistry has hitherto not been studied in detail.[7] Recently, we

(1) For a review: Nakayama, J.; Sugihara, Y. *Top. Curr. Chem.* **1999**, *205*, 131.
(2) (a) Nakayama, J.; Nagasawa, H.; Sugihara, Y.; Ishii, A. *J. Am. Chem. Soc.* **1997**, *119*, 9077. (b) Nagasawa, H.; Sugihara, Y.; Ishii, A.; Nakayama, J. *Bull. Chem. Soc. Jpn.* **1999**, *72*, 1919.
(3) For reviews, see: (a) Nakayama, J.; Sugihara, Y. *Sulfur Rep.* **1997**, *19*, 349. (b) Nakayama, J. *Sulfur Rep.* **2000**, *22*, 123.
(4) For selenophene 1-oxides and 1,1-dioxides, see: (a) Nakayama, J.; Matsui, T.; Sugihara, Y.; Ishii, A.; Kumakura, S. *Chem. Lett.* **1996**, 269. (b) Matsui, T.; Nakayama, J.; Sato, N.; Sugihara, Y.; Ishii, A.; Kumakura, S. *Phosphorus, Sulfur Silicon Relat. Elem.* **1996**, *118*, 227. (c) Umezawa, T.; Sugihara, Y.; Ishii, A.; Nakayama, J. *J. Am. Chem. Soc.* **1998**, *120*, 12351.
(5) (a) Pouzet, P.; Erdelmeier, I.; Ginderow, D.; Mornon, J.-P.; Dansette, P.; Mansuy, D. *J. Chem. Soc., Chem. Commun.* **1995**, 473. (b) Pouzet, P.; Erdelmeier, I.; Ginderow, D.; Mornon, J.-P.; Dansette, P.; Mansuy, D. *J. Heterocycl. Chem.* **1997**, *34*, 1567. (c) Nakayama, J.; Yu. T.; Sugihara, Y.; Ishii, A. *Chem. Lett.* **1997**, 499. (d) Furukawa, N.; Zhang, S.-Z.; Horn, E.; Takahashi, O.; Sato, S. *Heterocycles* **1998**, *47*, 793.
(6) (a) Naperstkow, A. M.; Macaulay, J. B.; Newlands, M. J.; Fallis, A. G. *Tetrahedron Lett.* **1989**, *30*, 5077. (b) Treiber, A.; Dansette, P. M.; Amri, H. E.; Girault, J.-P.; Ginderow, D.; Mornon, J.-P.; Mansuy, D. *J. Am. Chem. Soc.* **1997**, *119*, 1565. (c) Li, Y.-Q.; Thiemann, T.; Sawada, T.; Mataka, S.; Tashiro, M. *J. Org. Chem.* **1997**, *62*, 7926. (d) Li, Y.-Q.; Thiemann, T.; Mimura, K.; Sawada, T.; Mataka, S.; Tashiro, M. *Eur. J. Org. Chem.* **1998**, 1841.
(7) Nakayama, J. *Bull. Chem. Soc. Jpn.* **2000**, *73*, 1.

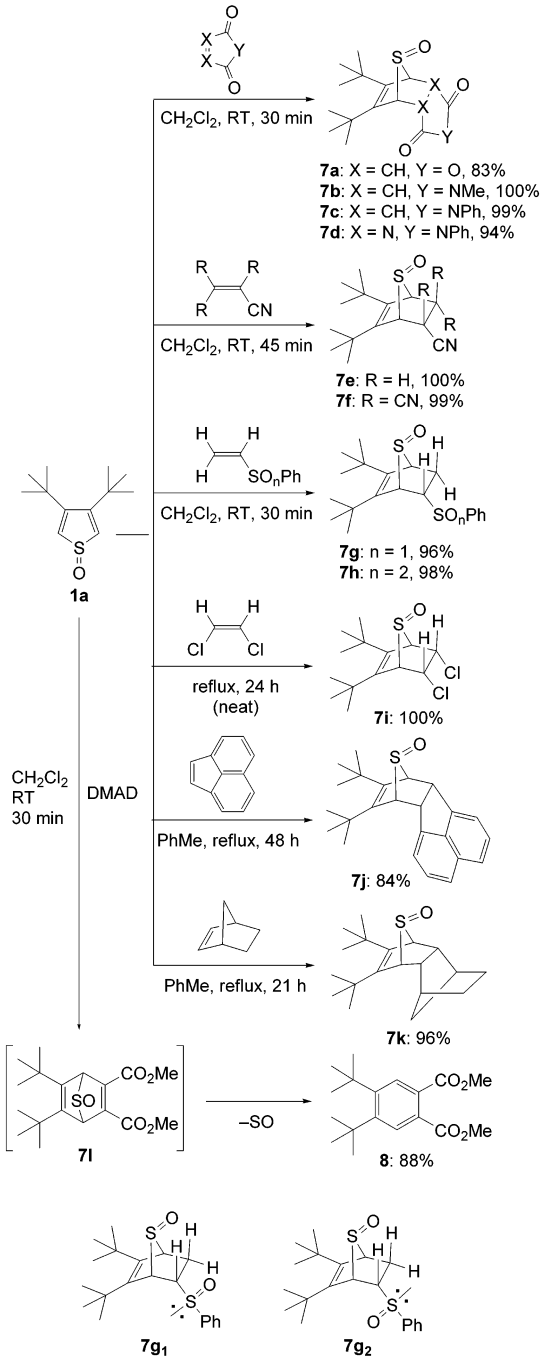
have obtained some thermally stable thiophene 1-oxides such as **1a**[5c] and a series of thiophene 1-imides such as **3a**.[8] For these compounds, the presence of two bulky substituents, such as *tert*-butyl, makes them stable enough to be handled under ordinary experimental conditions; otherwise, they might undergo [2+4]-self-dimerizations. X-ray crystallographic analyses showed that the molecular structures of **1a**[5c] and **3a**[8a,c] are similar to each other (Figure 1). Thus, **1a** and **3a** would serve as good substrates for the investigation of π-face selectivity in Diels−Alder reactions. Previously, the cycloaddition of a tetrachlorothiophene 1-imide (**3b**) with acenaphthylene was investigated; however, the stereochemical course of the reaction was not determined because the initial adduct extruded $EtO_2CN{=}S$ spontaneously to give **6** as the final product.[9] The synthesis[10] and the Diels−Alder reaction[11] of thiophene 1,1-dioxide (**2a**) were investigated previously by us in detail. We have now investigated (1) Diels−Alder reactions of **1a** and their stereochemical course, (2) Diels−Alder reactions of **3a** and their stereochemical course, and (3) comparison of the reactivities of **1a**, **2a**, and **3a** as dienes in Diels−Alder reactions.



Results and Discussion

Diels−Alder Reactions of Thiophene 1-Oxide 1a. Results of the Diels−Alder reactions of **1a** with a variety of dienophiles are summarized in Scheme 1. All of the Diels−Alder reactions, with one exception, produced the single diastereomer nearly quantitatively. Only the reaction with phenyl vinyl sulfoxide gave a 1:1 separable diastereomeric mixture of $\mathbf{7g_1}$ and $\mathbf{7g_2}$. The structures of **7a**, **7b**, and **7k** were determined unambiguously by X-ray crystallographic analyses as shown later. X-ray crystallographic analyses of other products were not performed; their structures were assigned as the *syn*-adducts to the S=O bond by taking the structures of **7a**, **7b**, and **7k** into account and by comparison of the NMR data with those of **7a**, **7b**, and **7k**. The *endo*-mode stereochemistry of the adducts was determined by inspection of the coupling constant values between H_a and H_b (J = 1.8−3.9 Hz for **7a**−**c**, **e**, **g**−**j**) in the ^{1}H NMR spectra (Figure 2); more smaller values (nearly zero) would be expected for the *exo*-mode adducts where dihedral angles become about 76°.[12] Thus, the results lead to the conclusion that the Diels−Alder reactions take place exclusively in an *endo*-

Scheme 1



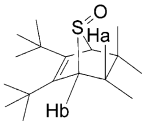
(8) (a) Otani, T.; Sugihara, Y.; Ishii, A.; Nakayama, J. *Tetrahedron Lett.* **1999**, *40*, 5549. (b) Otani, T.; Sugihara, Y.; Ishii, A.; Nakayama, J. *Tetrahedron Lett.* **2000**, *41*, 8461. (c) Nakayama, J.; Otani, T.; Sugihara, Y.; Sano, Y.; Ishii, A.; Sakamoto, A. *Heteroat. Chem.* **2001**, *12*, 333.

(9) (a) Meth-Cohn, O.; van Vuuren, G. *J. Chem. Soc., Perkin Trans. 1* **1986**, 233. (b) Dillen, J. L. M.; Meth-Cohn, O.; van Vuuren, G. *J. Chem. Soc., Perkin Trans. 1* **1987**, 2659.

(10) Nakayama, J.; Yamaoka, S.; Hoshino, M. *Tetrahedron Lett.* **1988**, *29*, 1161.

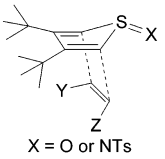
(11) (a) Nakayama, J.; Yamaoka, S.; Nakanishi, T.; Hoshino, M. *J. Am. Chem. Soc.* **1988**, *110*, 6598. (b) Nakayama, J.; Hirashima, A. *Heterocycles* **1989**, *29*, 1241−1242. (c) Nakayama, J.; Hirashima, A. *J. Am. Chem. Soc.* **1990**, *112*, 7648. (d) Nakayama, J.; Hasemi, R.; Yoshimura, K.; Sugihara, Y.; Yamaoka, S. *J. Org. Chem.* **1998**, *63*, 4912.

(12) Marchand, A. P.; Rose, J. E. *J. Am. Chem. Soc.* **1968**, *90*, 3724.



J_{Ha-Hb} = 1.8-3.9 Hz
for the **7a-c**, **e**, **g-j**

Figure 2.



X = O or NTs

Figure 3.

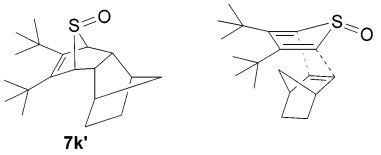


Figure 4.

mode with 100% π-face selectivity, in which dienophiles add to **1a** at the *syn*-π-face relating to the S═O bond (Figure 3; X = O).

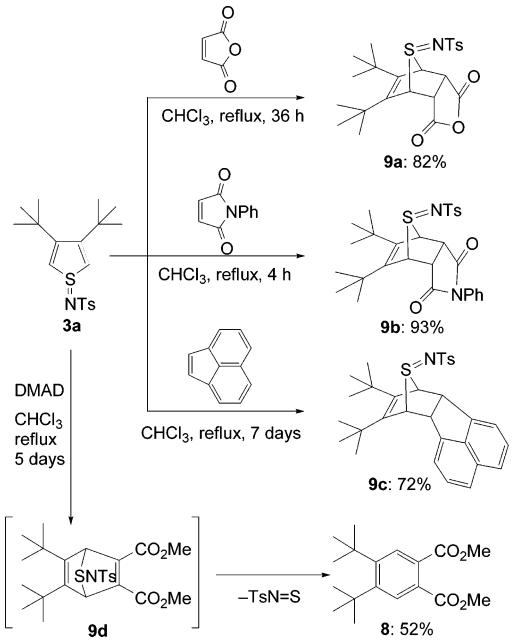
Furthermore, the following would be worthy of comments. The reactions of **1a** with a variety of dienophiles, carrying strongly electron-withdrawing substituent(s), took place quickly at room temperature and are complete within 45 min; see the reactions with maleic anhydride, *N*-methyl- and *N*-phenymaleimide (NMM and NPM), 4-phenyl-1,2,4-triazoline-3,5-dione (PTAD), acrylonitrile, tetracyanoethylene (TCNE), phenyl vinyl sulfoxide, and phenyl vinyl sulfone. As previously reported, the Diels−Alder reactions of 1,1-dioxide **2a** with maleic anhydride, NPM, PTAD, phenyl vinyl sulfoxide, and phenyl vinyl sulfone required heating in boiling *o*-dichlorobenzene to take place at a practical rate.[11c,d] Therefore, **1a** is a far more reactive diene than **2a** toward these dienophiles. This conclusion on the relative reactivity would be generally true for the Diels−Alder reactions of thiophene 1-oxides and 1,1-dioxides and not be limited to the present case. Even the weakly activated dienophile *cis*-1,2-dichloroethylene reacted with **1a**, although it was used in large excess as the solvent. Reactions of **1a** with angle-strained alkenes, acenaphthylene and norbornene, took place at a practical rate in boiling toluene. The reaction with the latter gave the single diastereomer **7k** in 96% yield, although the formation of eight diastereomers including **7k′** is possible. The sole formation of **7k** shows that the reaction took place exclusively at the less crowded *exo*-π-face of norbornene[13] and at the *syn*-π-face of **1a** in an *endo*-mode (Figure 4).

The reaction of equimolar amounts of **1a** and dimethyl acetylenedicarboxylate (DMAD) proceeded at room temperature with spontaneous extrusion of sulfur monoxide (SO) from the initial adduct **7l** to give an *o*-di-*tert*-butylbenzene **8** in 88% yield. Application of the reaction to other alkynic dienophiles would provide a convenient synthesis of this class of congested compounds, which are otherwise difficult to prepare.[11d] Incidentally, the synthesis of **8** by Diels−Alder reaction of **2a** with DMAD required prolonged heating in refluxing *o*-dichlorobenzene and the use of excess DMAD.[11a,d] The reaction also might provide an efficient method for generation of SO, whose formation by thermolysis of a cyclic trisulfide-2-oxide was recently communicated.[14]

Diels−Alder Reactions of Thiophene 1-Imide 3a. The Diels−Alder reaction of **3a** with maleic anhydride proceeded much slower than that of **1a**. The reaction required heating in refluxing $CHCl_3$ for 36 h to give an 82% yield of the single diastereomeric adduct **9a**. The structure of **9a** was determined by X-ray crystallographic analysis as described later. 1-Imide **3a** also reacted with NPM and acenaphthylene in refluxing $CHCl_3$ to give the single diastereomer **9b** and **9c** in 93% and 72% yields, respectively. The structures of **9b** and **9c** were determined in a manner similar to that applied to the adducts of **1a**.

The reaction of **3a** with DMAD took place, when heated in refluxing $CHCl_3$ for a prolonged period, to give **8** in 52% yield through extrusion of TsN═S[15] of the initial adduct **9d**.

These results lead to the conclusions that (1) Diels−Alder reactions of **3a** also take place with 100% π-face selectivity (addition at the *syn*-π-face relating to the S═NTs bond) in an *endo*-mode (Figure 3; X = NTs) and (2) the 1-oxide **1a** is a more reactive diene for Diels−Alder reactions than the 1-imide **3a**, which is in turn a more reactive diene than the 1,1-dioxide **2a**.



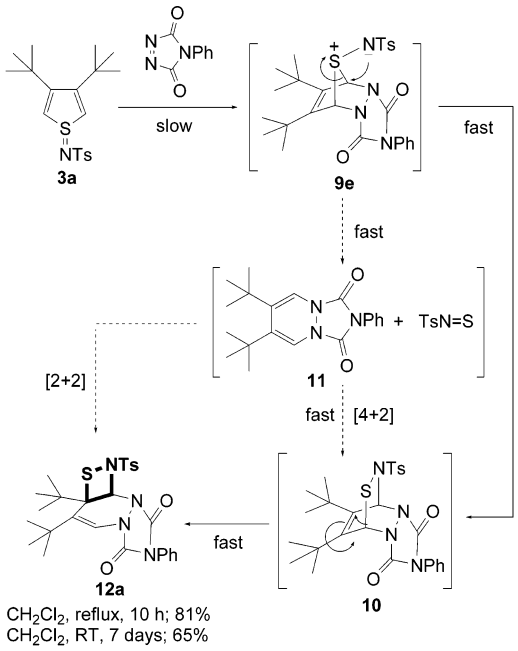
Diels−Alder Reactions of 1-Imides with PTAD; Unexpected Formation of 1,2-Thiazetidines. In contrast to the reaction of **1a** with PTAD which produced the expected Diels−Alder adduct **7d**, the reaction of **3a** with PTAD in boiling CH_2Cl_2 afforded a 1,2-thiazetidine derivative (**12a**) in 81% yield. The same product **12a** was also formed in 65% yield even when

(13) For the *exo*-selection and enhanced reactivities of norbornene, see: (a) Schleyer, P. v. R. *J. Am. Chem. Soc.* **1967**, *89*, 701. (b) Brown, H. C.; Hammar, W. J.; Kawakami, J. H.; Rothberg, I.; Vander Jagt, D. L. *J. Am. Chem. Soc.* **1967**, *89*, 6381. (c) Inagaki, S.; Fujimoto, H.; Fukui, K. *J. Am. Chem. Soc.* **1976**, *98*, 4054. (d) Huisgen, R.; Ooms, P. H. J.; Mingin, M.; Allinger, N. L. *J. Am. Chem. Soc.* **1980**, *102*, 3951.

(14) Grainger, R. S.; Procopio, A.; Steed, J. W. *Org. Lett.* **2001**, *3*, 3565.

(15) Chemical trapping of EtO_2CN═S, generated from the [4+2] adduct of **3b** with dienophiles, was previously reported.[9b]

the reaction was carried out at room temperature. The structure of **12a** was determined by X-ray diffraction analysis as described later. The reaction would form the adduct **9e** initially probably in an *endo*-mode with π-face selectivity. Electrostatic repulsions between lone-pair electrons of the three nitrogen atoms would make **9e** thermally unstable. Thus, **9e** rearranges to a less angle-strained bicyclo[2.2.2] ring system **10**. The lone-pair electron repulsions among the four heteroatoms still exist in **10**, which causes the further rearrangement of **10** to the final product **12a** despite increasing angle strains. Neither **9e** nor **10** was detected by ^{1}H NMR, indicating that the rearrangements, **9e** to **10** and **10** to **12a**, take place quickly. A less probable mechanism involves the decomposition of **9e** to **11** and TsN=S. [2+4] Cycloaddition of **11** with TsN=S would produce **10**, or their [2+2] cycloaddition would lead to **12a** directly. However, if this is the case, the [4+2] cycloadduct of **3a** with TsN=S should be formed.



Four-membered saturated heterocycles **12**−**14** which contain two heteroatoms at vicinal positions in their ring are an interesting class of compounds.[16] The electrostatic repulsions between the lone pair electrons of heteroatoms destabilize these ring systems, rendering their synthesis very difficult. Tetramethyl-1,2-oxathietane[17] and dithiatopazine[18] are the only examples of the isolable S-unoxidized 1,2-oxathietane **13** and 1,2-dithietane **14**, respectively. As for the nitrogen analogue, the successful synthesis of S-unoxidized 1,2-thiazetizines **12** has hitherto not been reported, whereas a few syntheses of **15** and a great number of syntheses of **16** (β-sultam) are known.[19] Thus,

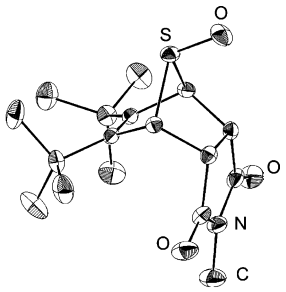
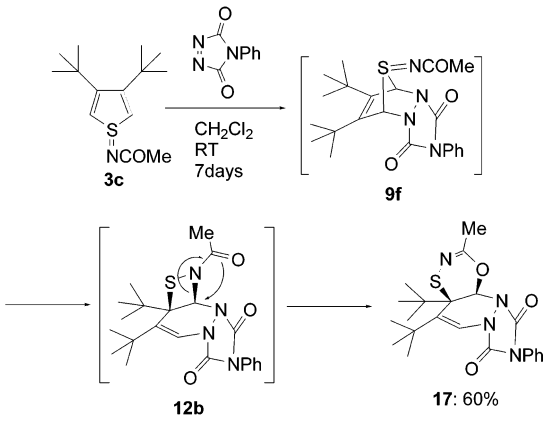


Figure 5. Molecular structure of **7b**.

12a provides the first example of S-unoxidized 1,2-thiazetidine that permitted synthesis and isolation.

When *N*-acetyl derivative **3c** was used in place of **3a** for the reaction with PTAD, a further rearrangement of the 1,2-thiazetidine **12b**, probably formed through rearrangement of the initial adduct **9f**, took place at room temperature to give a 5*H*,6*H*-1,4,3-oxathiazine **17** as the final product in 60% yield. Any intermediates, including **12b**, were neither isolated nor detected by ^{1}H NMR, suggesting that each rearrangement occurs rapidly. An analogy of the rearrangement of **12b** to **17**, where the relief from angle strains serves as a driving force, is found in the ring-expansion of 1-acetylaziridines to 2-methyl-4,5-dihydrooxazoles.[20]



X-ray Crystallographic Analyses of the Adducts. Molecular structures of the adducts **7b**, **7k**, and **9a** are given in Figures 5−7, respectively. Results of the X-ray analysis of **7a** are suitable for the structure elucidation, but not suitable for the discussion of the molecular structure (see Table 1). A brief discussion on the molecular structure of these compounds is made below by using **7k** as the representative example. The C_1-C_2 double bond length of 1.355(3) Å is slightly longer than that of ethylene, 1.33 Å. The $C_1-C_2-C_3$ bond angle, 133.0-(2)°, is much larger than the C−C−H bond angle of ethylene, 121.7°, and is almost equal to the corresponding bond angle of (*Z*)-1,2-di-*tert*-butylethylene (135°).[21,22] The double bond part

(16) For a review: Nakayama, J.; Ishii, A. *Adv. Heterocycl. Chem.* **2000**, *77*, 221.
(17) Lown, J. W.; Koganty, R. R. *J. Am. Chem. Soc.* **1986**, *108*, 3811.
(18) (a) Nicolaou, K. C.; Hwang, C.-K.; Duggan, M. E.; Carroll, P. J. *J. Am. Chem. Soc.* **1987**, *109*, 3801. (b) Nicolaou, K. C.; Hwang, C.-K.; DeFrees, S.; Stylianides, N. A. *J. Am. Chem. Soc.* **1988**, *110*, 4868. (c) Nicolaou, K. C.; DeFrees, S. A.; Hwang, C.-K.; Stylianides, N.; Carroll, P. J.; Snyder, J. P. *J. Am. Chem. Soc.* **1990**, *112*, 3029.
(19) (a) Timberlake, J. W.; Elder, E. S. In *Comprehensive Heterocyclic Chemistry*; Lwowski, W., Vol. Ed.; Pergamon Press: Oxford, 1984; Vol. 7, Chapter 5.15. (b) Harris, P. A. In *Comprehensive Heterocyclic Chemistry II*; Padwa, A., Vol. Ed.; Pergamon Press: Oxford, 1996; Vol. 1, Chapter 1.32.
(20) Burnstein, I. J.; Fanta, P. E.; Green, B. S. *J. Org. Chem.* **1970**, *35*, 4084.
(21) Robinson, M. J. T. *Organic Stereochemistry*; Oxford University Press: Oxford, 2000; p 17.

Table 1. Crystallographic Data of the Adducts

	3a	7a	7b	7k	9a	12a	17
formula	$C_{19}H_{27}NO_2S_2$	$C_{16}H_{22}O_4S$	$C_{17}H_{25}NO_3S$	$C_{19}H_{30}OS$	$C_{23}H_{29}NO_5S_2$	$C_{27}H_{32}N_4O_4S$	$C_{22}H_{28}N_4O_3S$
fw	365.56	310.41	323.46	306.51	463.62	540.71	428.56
crystal system	triclinic	tetragonal	monoclinic	monoclinic	monoclinic	monoclinic	triclinic
color	colorless	colorless	colorless	colorless	colorless	colorless	colorless
crystal habit	needle	cube	cube	cube	needle	plate	cube
spcae group	$P\bar{1}$	$P4/n$	$P2_1/c$	$P2_1/c$	$P2_1/c$	$P2_1/c$	$P\bar{1}$
crystal size, mm^3	0.29 × 0.08 × 0.08	0.30 × 0.27 × 0.23	0.20 × 0.18 × 0.18	0.30 × 0.23 × 0.20	0.18 × 0.10 × 0.10	0.26 × 0.16 × 0.16	0.19 × 0.14 × 0.10
a, Å	9.6890(8)	21.4715(12)	8.7860(4)	9.0370(5)	7.2296(14)	7.6880(7)	7.8070(7)
b, Å	14.1150(13)	21.4715(12)	8.8980(4)	15.5810(9)	21.916(4)	28.758(2)	10.9520(6)
c, Å	15.610(2)	15.3680(11)	21.6100(13)	13.2450(10)	15.376(4)	12.2780(14)	14.1090(11)
α, deg	105.820(4)						66.974(5)
β, deg	100.184(3)		100.686(2)	106.16(18)	105.03(6)	92.760(3)	82.138(4)
γ, deg	98.048(3)						85.308(6)
V, Å^3	1981.3(4)	7085.0(8)	1660.13(15)	1693.1(2)	2352.9(9)	2711.4(5)	1099.27(14)
Z	4	16	4	4	4	4	2
D_{calc}, g/cm^3	1.226	1.164	1.294	1.202	1.309	1.325	1.295
μ, mm^{-1}	0.279	0.194	0.207	0.189	2.332	0.236	0.178
$2\theta_{max}$, deg	54.1	54.5	54.1	54.2	140.6	54.7	54.0
total measured	7247	7634	10 633	3614	4990	5786	4037
unique reflections	7247	7374	3405	3492	3912	5671	4037
observed reflections	2776 [$I > \sigma 2(I)$]	2620 [$I > \sigma 2(I)$]	2890 [$I > \sigma 2(I)$]	2060 [$I > \sigma 2(I)$]	3395 [$I > \sigma 2(I)$]	2461 [$I > \sigma 2(I)$]	2247 [$I > \sigma 2(I)$]
no. of parameters	419	380	299	191	290	335	384
R	0.0785	0.0991	0.0403	0.0633	0.0877	0.0832	0.0593
R_w	0.1585	0.2441	0.0966	0.1575	0.2103	0.1594	0.1209
GOF	1.033	1.038	1.029	0.999	1.077	1.021	1.012
temp, K	298	153	153	298	298	298	153
final diff Four. map (e Å^{-3})	0.372, −0.364	1.711, −0.294	0.348, −0.340	0.271, −0.236	0.404, −0.440	0.976, −0.268	0.240, −0.304

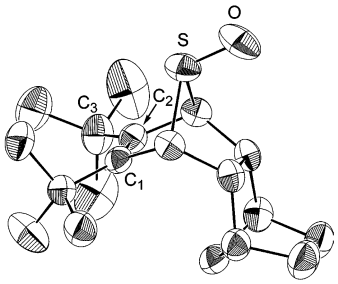


Figure 6. Molecular structure of **7k**.

has a nearly planar structure (sum of bond angles around C_2; 359.9°), indicating that steric repulsions between *tert*-butyl groups are mainly avoided by enlargement of the bond angles, in addition to slight elongation of the bond length. The same conclusion is also reached for the double bond part of the adducts **7b** and **9a**. Incidentally, the two *tert*-butyl groups of **7b**, **7k**, and **9a** appear as a sharp singlet in the ^{1}H NMR spectra, revealing that the *tert*-butyl groups are freely rotating at room temperature.

Figure 8 shows a molecular structure of the thiazetidine **12a**. The thiazetidine ring is fused in a *cis*-manner to the six-membered ring as was expected from the mechanism of its formation. The relevant bond lengths and angles data are summarized in Figure 9. A number of reports have appeared on X-ray crystallographic analyses of 1,2-thiazetidine 1,1-dioxides **16**.[23] The C_2-S_1 (1.874(4) Å) and $N-S_1$ (1.791(4) Å)

(22) The C(*t*-Bu)−C═C angle and the C═C bond length are 131.4° and 1.365 Å, respectively, for 1,2-di-*tert*-butyl-3,3,5,5-tetramethylcyclopentene: Ishii, A.; Tsuchiya, C.; Shimada, T.; Furusawa, K.; Omata, T.; Nakayama, J. *J. Org. Chem.* **2000**, *65*, 1799.

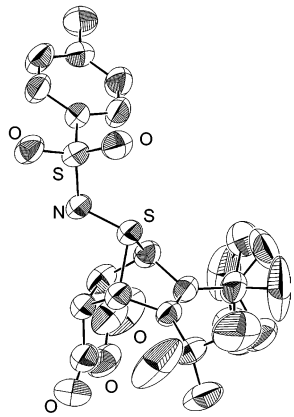


Figure 7. Molecular structure of **9a** (one of the *tert*-butyl groups is disordered).

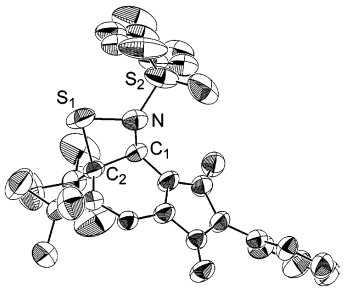


Figure 8. Molecular structure of **12a**.

bonds of **12a** are much longer than the corresponding C−S (1.761−1.780 Å) and N−S (1.642−1.698 Å) bonds of **16**[23] and also longer than the common C−S (1.819 Å) and N−S bond (1.765 Å) lengths.[24] As for the bond angles, any particular

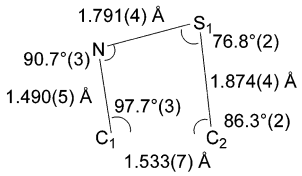


Figure 9. Relevant bond lengths and bond angles data of the thiazetidine ring of **12a**.

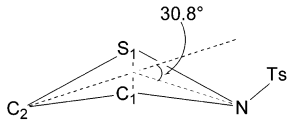


Figure 10. Puckered structure of the thiazetidine ring of **12a**.

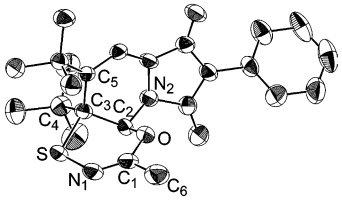


Figure 11. Molecular structure of **17**.

difference was not found between **12a** and **16**. The sum of the bond angles, $\angle S_1-N-S_2 + \angle C_1-N-S_1 + \angle S_2-N-C_1$, amounts to 328.0° in **12a**. This value, which is equal to the sum of the three H−C−H bond angles of methane (328°), is indicative of sp^3-hybridization of the nitrogen atom.

The thiazetidine ring of **12a** is puckered with a puckering angle of 30.8° and a $C_1-C_2-S_1-N$ dihedral angle of 19.6° (Figure 10). The puckering angle of **12a** is greater than that of cyclobutane (28°),[25] where the torsional strain is reduced by puckering. The most significant factor, which renders heterocycles **12**−**14** thermally labile, is the repulsive interactions between lone pair electrons of heteroatoms at vicinal positions.[16] Thus, the origin of the puckered conformation of **12a** would be partly attributed to the relief from such repulsive interactions.

A molecular structure of theoxathiazine **17** is given in Figure 11. Preparation of S-unoxidized 5*H*,6*H*-1,4,3-oxathiazines has hitherto not been reported,[26] and thus this is the first example of X-ray crystallographic analysis of this class of heterocycle. The two six-membered rings of **17** are fused cis to each other. The oxathiazine ring adopts a half-chair conformation with large dihedral angles of 39.2(2)° and −64.7(2)° for $N_1-S-C_3-C_2$ and $O-C_2-C_3-S$, respectively, and a small dihedral angle of −3.9(3)° for $O-C_1-N_1-S$. The C_3-C_4 bond length is elongated to 1.602(5) Å to reduce steric repulsions between the adjacent *tert*-butyl groups. The C_3-S bond length (1.852(3) Å) is also elongated as compared to the common $C(sp^3)-S$ bond length (1.819 Å), while the $S-N_1$ (1.679(3) Å) bond length is shorter than the common $N(sp^3)-S$ (1.765 Å) bond length.[24]

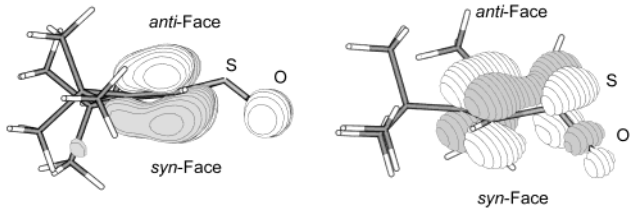


Figure 12. Nonequivalent orbital extension of π-HOMO (left) and π-LUMO (right) of **1a**.

Origin of the π-Face Selectivity for the Diels−Alder Reactions. π-Face selectivity in Diels−Alder reactions has been attracting much attention both from a theoretical and from a synthetic point of view. It has been investigated most extensively by using C5-substituted cyclopentadienes as the substrate.[27] Diels−Alder reactions of thiophene 1-oxides with alkenic dienophiles have provided another excellent model for investigating the π-face selectivity. The calculations, carried out at the RHF and MP2 levels with the 6-31G(d) basis set, predicted that the reaction of thiophene 1-oxide with ethylene takes place more preferably in a *syn*-addition mode relating to the S−O bond than in an *anti*-addition mode both kinetically and thermodynamically.[5d,28] Indeed, the pioneering work showed that 2,5-dimethylthiophene 1-oxide, generated in situ by oxidation of 2,5-dimethylthiophene with MCPBA, undergoes Diels−Alder reactions with electron-deficient dienophiles in a *syn*-mode relating to the S−O bond.[6a] The Diels−Alder reactions of 2,5-bis(trimethylsilyl)thiophene 1-oxide with electron-deficient alkenic dienophiles were also established to take place in a *syn*-mode.[5d] BF_3 catalysis in the oxidative cycloaddition of polysubstituted thiophenes also produced [4+2] adducts in a *syn*-mode.[6c,d]

The present study showed that the 1-oxide **1a** undergoes Diels−Alder reactions at its *syn*-face not only with electron-deficient dienophiles but also with angle-strained dienophiles. The *syn*-π-face selectivity in Diels−Alder reactions of thiophene 1-oxides has been explained by the orbital mixing rule, that is, nonequivalent orbital extension;[13c] the distortion from the planarity makes π-HOMO lobes greater at the *syn*- than the *anti*-π-face and thus favors the reactions at the *syn*-face.[5d,29] Indeed, also for **1a**, B3LYP/6-31G(d) calculations[30] predicted that the π-HOMO lobes are slightly greater at the *syn*- than the *anti*-π-face (Figure 12). This will explain the observed *syn*-stereochemistry of the reactions with electron-deficient dienophiles. On the other hand, the calculations predicted that the

(23) (a) Meyle, E.; Otto, H.-H.; Kratky, C. *Monatsh. Chem.* **1985**, *116*, 493. (b) Meyle, E.; Keller, E.; Otto, H.-H. *Liebigs Ann. Chem.* **1985**, 802. (c) Chiaroni, A.; Riche, C.; Loiseau, P.; Bonnafous, M.; Adam, Y. *Acta Crystallogr., Sect. C* **1985**, *41*, 1265. (d) Belskii, V. K.; Bodrikov, I. V.; Michurin, A. A.; Chumakova, L. I.; Zhiboderov, A. V. *Tetrahedron Lett.* **1985**, *26*, 5689. (e) Mueller, M.; Meyle, E.; Paulus, E. F.; Plagge, H.; Otto, H.-H. *Liebigs Ann. Chem.* **1989**, 975.
(24) Allen, F. H.; Kennard, O.; Watson, D. G.; Brammer, L.; Orpen, A. G.; Taylor, R. *J. Chem. Soc., Perkin Trans. 2* **1987**, S1−S19.
(25) Egawa, T.; Fukuyama, T.; Yamamoto, S.; Takabayashi, F.; Kambara, H.; Ueda, T.; Kuchitsu, K. *J. Chem. Phys.* **1987**, *86*, 6018.
(26) Riddell, F. G.; Royles, B. J. L. In *Comprehensive Heterocyclic Chemistry II*; Boulton, A. J., Vol. Ed.; Pergamon Press: Oxford, 1996; Vol. 6, Chapter 6.19.
(27) For a review: Oppolzer, W. In *Comprehensive Organic Synthesis*; Paquette, L. A., Vol. Ed.; Pergamon Press: Oxford, 1991; Vol. 5, Chapter 4.1.
(28) For other calculation studies, see: (a) Werstiuk, N. H.; Ma, J. *Can. J. Chem.* **1994**, *72*, 2493. (b) Jursic, B. S. *J. Mol. Struct. (THEOCHEM)* **1998**, *454*, 105. (c) Jursic, B. S. *J. Mol. Struct. (THEOCHEM)* **1998**, *459*, 215.
(29) Explanation by the Cieplak effect was proposed, where the lone-pair electron orbital at the sulfur atom stabilizes the vacant σ^* orbitals of the developing incipient σ-bonds rather than would any orbitals associated with the S−O bond.[6c] For a review on the Cieplak effect, see: Cieplak, A. S. *Chem. Rev.* **1999**, *99*, 1265.
(30) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Baboul, A. G.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, revision A.7; Gaussian, Inc.: Pittsburgh, PA, 1998.

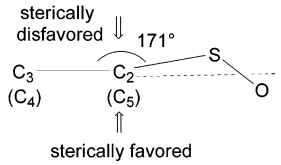


Figure 13.

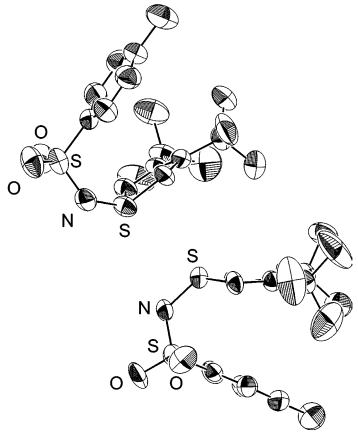


Figure 14. Molecular structure of **3a** (the analysis was performed on two independent molecules).

π-LUMO lobes are slightly greater at the *anti*- than at the *syn*-π-face (Figure 12). Furthermore, the calculations predicted that the energy difference (4.25 eV) between π-LUMO$_{\mathbf{1a}}$ (−1.56 eV) and HOMO$_{\text{acenaphthylene}}$ (−5.81 eV) is smaller than the energy difference (4.55 eV) between π-HOMO$_{\mathbf{1a}}$ (−6.44 eV) and LUMO$_{\text{acenaphthylene}}$ (−1.89 eV). A similar energy difference was predicted for the norbornene case: the 4.72 eV difference between π-LUMO$_{\mathbf{1a}}$ and HOMO$_{\text{norbornene}}$ (−6.28 eV) and the 7.14 eV difference between π-HOMO$_{\mathbf{1a}}$ and LUMO$_{\text{norbornene}}$ (0.70 eV). These calculations indicate that the Diels−Alder reactions with norbornene and acenaphthylene are LUMO$_{\text{diene}}$-controlled, where the π-face selectivity should be changed from *syn* to *anti*. We therefore should consider another factor that influences the stereochemical course of the Diels−Alder reactions.

The 1-oxide **1a** has a shallow V-shaped geometry at the C_2 (C_5) as shown in Figure 13. This means that the *syn*-π-face with respect to the S−O bond is more open for the Diels−Alder reactions than is the *anti*-face, making the reaction at the *syn*-π-face sterically more favorable. We propose the steric effect as one of the factors that influences the stereochemical course of the reactions.

The present study clarified for the first time that the thiophene 1-imide also undergoes Diels−Alder reactions at its *syn*-π-face not only with electron-deficient dienophiles but also with angle-strained alkene acenaphthylene. Interestingly, thiophene 1-imide **3a** exists in the crystalline state in a conformation in which the thiophene ring and benzene ring are placed in a face-to-face orientation (Figure 14). The calculations also predicted that the most stable conformation of **3a** is the one given in Figure 15, a conformation similar to that obtained by X-ray crystallographic analysis. The face-to-face conformation, in which the *syn*-π-face of the thiophene ring is sheltered by the benzene ring, would render the reaction at the *syn*-π-face unfavorable. Nevertheless, the reaction took place at the *syn*-face. This indicates that the free rotation, which expels the benzene ring to the opposite

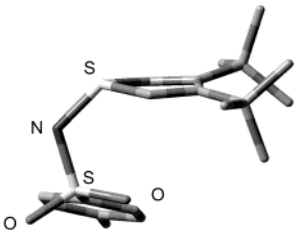


Figure 15. Predicted most stable conformation of **3a** by calculations.

direction, takes place in solution. The calculations also predicted that the Diels−Alder reactions of **3a** with electron-deficient alkenes are of normal type, whereas that with acenaphthylene is of inverse type with the energy difference (3.93 eV) between π-LUMO$_{\mathbf{3a}}$ (−1.88 eV) and HOMO$_{\text{acenaphthylene}}$ (−5.81 eV), and the energy difference (4.77 eV) between π-HOMO$_{\mathbf{3a}}$ (−6.66 eV) and LUMO$_{\text{acenaphthylene}}$ (−1.89 eV). The observed stereochemistry of **3a** would be explained in the same manner as that described with **1a**.

In conclusion, we showed that both 1-oxide **1a** and 1-imide **3a** undergo Diels−Alder reactions at their *syn*-π-face not only with electron-deficient dienophiles but also with angle-strained alkenes. We also succeeded in the first synthesis of S-unoxidized 1,2-thiazetidine **12a**. We are currently investigating the stereochemistry of the Diels−Alder reactions of **1a** and **3a** with highly electron-rich alkenes, where the π-face selectivity might be changed from *syn* to *anti*.

Experimental Section

Solvents were purified and dried in the usual manner. Silica gel column chromatography was performed on silica gel 7734 (Merck, 70-230 mesh) or silica gel 60 N (Kanto, 63-210 mesh). Melting points were determined on a Mel-Temp capillary tube apparatus and are uncorrected. ^{1}H and ^{13}C NMR spectra (400 MHz for ^{1}H NMR and 100.6 MHz for ^{13}C NMR) were recorded on a Bruker ARX400 or a Bruker AM400 spectrometer using $CDCl_3$ as the solvent, unless otherwise stated, with TMS as the internal standard. IR spectra were taken for a KBr disk on a Perkin-Elmer System 2000 FT-IR spectrophotometer. Elemental analyses were performed by the Chemical Analysis Center of Saitama University.

Diels−Alder Reactions of Thiophene 1-Oxide 1a. (a) With Maleic Anhydride. A mixture of 42 mg (0.2 mmol) of **1a** and 20 mg (0.2 mmol) of maleic anhydride in CH_2Cl_2 (10 mL) was stirred for 30 min at room temperature. The reaction mixture was evaporated, and the resulting residue was washed with a small amount of hexane to give 53 mg (83%) of the adduct **7a**: mp 130−131 °C (from cyclohexane). ^{1}H NMR: δ 1.28 (s, 18H), 4.24 (dd, J = 2.8, 2.1 Hz, 2H), 4.46 (dd, J = 2.8, 2.1 Hz, 2H). ^{13}C NMR: δ 32.4, 34.6, 46.4, 67.9, 143.6, 170.2. IR: 1861, 1780 (C═O), 1077 (S═O) cm^{-1}. Anal. Calcd for $C_{16}H_{22}O_4S$: C, 61.91; H, 7.14. Found: C, 61.84; H, 7.48.

(b) With *N*-Methylmaleimide (NMM). The reaction of 212 mg (1.0 mmol) of **1a** and 111 mg (1.0 mmol) of NMM in CH_2Cl_2 (5 mL) for 30 min at room temperature gave 323 mg (100%) of the adduct **7b**: mp 191−192 °C (from CH_2Cl_2/hexane). ^{1}H NMR: δ 1.23 (s, 18H), 2.93 (s, 3H), 3.95 (dd, J = 2.8, 1.9 Hz, 2H), 4.38 (dd, J = 2.8, 1.9 Hz, 2H). ^{13}C NMR: δ 24.6, 32.2, 34.1, 44.9, 66.7, 142.3, 175.5. IR: 1781, 1698 (C═O), 1074 (S═O) cm^{-1}. Anal. Calcd for $C_{17}H_{25}NO_3S$: C, 63.13; H, 7.79; N, 4.33. Found: C, 63.17; H, 7.86; N, 4.35.

(c) With *N*-Phenylmaleimide (NPM). The reaction of 212 mg (1.0 mmol) of **1a** and 182 mg (1.0 mmol) of NPM in CH_2Cl_2 (5 mL) for 30 min at room temperature gave 394 mg (99%) of the adduct **7c**: mp 238−239 °C (dec) (from CH_2Cl_2/hexane). ^{1}H NMR: δ 1.28 (s, 18H), 4.11 (dd, J = 2.7, 1.6 Hz, 2H), 4.46 (dd, J = 2.7, 1.6 Hz, 2H), 7.19−7.22 (m, 2H), 7.38−7.41 (m, 1H), 7.44−7.48 (m, 2H). ^{13}C NMR: δ

32.6, 34.5, 45.2, 67.4, 126.3, 128.8, 129.2, 131.6, 142.7, 175.8. IR: 1773, 1714 (C═O), 1083 (S═O) cm^{-1}. Anal. Calcd for $C_{22}H_{27}NO_3S$: C, 68.54; H, 7.06; N, 3.63. Found: C, 68.29; H, 7.01; N, 3.56.

(d) With *N*-Phenyl-1,3,5-triazoline-2,4-dione (PTAD). The reaction of 100 mg (0.47 mmol) of **1a** and 83 mg (0.47 mmol) of PTAD in CH_2Cl_2 (10 mL) for 30 min at room temperature gave 172 mg (94%) of the adduct **7d**: mp 218.5−219.5 °C (dec) (from CH_2Cl_2/hexane). ^1H NMR: δ 1.37 (s, 18H), 6.03 (s, 2H), 7.29−7.48 (m, 5H). ^{13}C NMR: δ 31.8, 34.7, 83.9, 126.3, 128.7, 129.2, 131.4, 143.0, 157.4. IR: 1790, 1733 (C═O), 1110 (S═O) cm^{-1}. Anal. Calcd for $C_{20}H_{25}N_3O_3S$: C, 61.99; H, 6.50; N, 10.84. Found: C, 62.08; H, 6.50; N, 10.83.

(e) With Acrylonitrile. The reaction of 100 mg (0.47 mmol) of **1a** and 29 mg (0.55 mmol) of acrylonitrile in CH_2Cl_2 (5 mL) for 10 min at room temperature gave 125 mg (100%) of the adduct **7e**: mp 146−148 °C (from CH_2Cl_2/hexane). ^1H NMR: δ 1.30 (s, 9H), 1.34 (s, 9H), 1.99 (dd, J = 13.4, 4.3 Hz, 1H), 2.87 (ddd, J = 13.4, 10.2, 3.2 Hz, 1H), 3.59 (ddd, J = 10.2, 4.3, 3.7 Hz, 1H), 3.99 (dd, J = 3.7, 3.2 Hz, 1H), 4.20 (dd, J = 3.2, 3.2 Hz, 1H). ^{13}C NMR: δ 26.4, 29.2, 31.9, 32.6, 33.8, 35.5, 66.0, 66.2, 121.0, 140.8, 145.6. IR: 2234 (C≡N), 1083 (S═O) cm^{-1}. Anal. Calcd for $C_{15}H_{23}NOS$: C, 67.88; H, 8.73; N, 5.28. Found: C, 67.97; H, 8.83; N, 5.13.

(f) With Tetracyanoethylene (TCNE). The reaction of 100 mg (0.47 mmol) of **1a** and 60 mg (0.47 mmol) of TCNE in CH_2Cl_2 (5 mL) for 45 min at room temperature gave 159 mg (99%) of the adduct **7f**: mp 267−268 °C (dec) (from CH_2Cl_2/hexane). ^1H NMR: δ 1.41 (s, 18H), 5.00 (s, 2H). ^{13}C NMR: δ 32.3, 35.7, 46.5, 73.6, 108.3, 110.6, 145.9. IR: 2356, 2339, 2253 (C≡N), 1105 (S═O) cm^{-1}. Anal. Calcd for $C_{18}H_{20}N_4OS$: C, 63.50; H, 5.92; N, 16.45. Found: C, 63.22; H, 5.95; N, 16.27.

(g) With Phenyl Vinyl Sulfoxide. A mixture of 100 mg (0.47 mmol) of **1a** and phenyl vinyl sulfoxide in CH_2Cl_2 (3 mL) was stirred for 10 min at room temperature. The reaction mixture was evaporated, and the resulting residue was chromatographed on a column of silica gel with Et_2O as the eluent to give the two diastereomers **7g$_1$** and **7g$_2$** in 96% combined yield. Diastereomer A (79 mg, 46%): mp 122−124 °C (from CH_2Cl_2/hexane). ^1H NMR: δ 1.30 (s, 9H), 1.37 (s, 9H), 2.14 (ddd, J = 13.4, 9.5, 3.7 Hz, 1H), 2.44 (dd, J = 13.4, 4.6 Hz, 1H), 3.76 (ddd, J = 9.5, 4.6, 3.4 Hz, 1H), 3.86 (dd, J = 3.7, 2.2 Hz, 1H), 4.26 (dd, J = 3.4, 2.2 Hz, 1H), 7.29−7.59 (m, 3H), 7.59−7.61 (m, 2H). ^{13}C NMR: δ 18.9, 31.8, 32.8, 33.8, 35.1, 63.0, 65.4, 67.0, 123.6, 129.1, 130.8, 138.7, 143.7, 144.2. IR: 1081 (S═O), 1036 (S═O) cm^{-1}. Anal. Calcd for $C_{20}H_{28}O_2S_2$: C, 65.89; H, 7.74. Found: C, 66.05; H, 7.95. The other diastereomer B (86 mg, 50%): mp 50−51 °C (from hexane). ^1H NMR: δ 1.31 (s, 9H), 1.42 (s, 9H), 1.45 (dd, J = 13.7, 4.4 Hz, 1H), 2.25 (ddd, J = 13.7, 9.5, 3.4 Hz, 1H), 3.86 (dd, J = 3.4, 2.4 Hz, 1H), 3.99 (ddd, J = 9.5, 4.4, 3.9 Hz, 1H), 4.49 (dd, J = 3.9, 2.4 Hz, 1H), 7.50−7.54 (m, 3H), 7.75−7.80 (m, 2H). ^{13}C NMR: δ 24.8, 31.7, 32.4, 33.7, 35.6, 65.3, 66.0, 66.4, 125.2, 129.3, 131.9, 141.3, 143.1, 144.9. IR: 1082 (S═O), 1045 (S═O) cm^{-1}. Anal. Calcd for $C_{20}H_{28}O_2S_2$: C, 65.89; H, 7.74. Found: C, 65.88; H, 7.80.

(h) With Phenyl Vinyl Sulfone. A mixture of 100 mg (0.47 mmol) of **1a** and 80 mg of phenyl vinyl sulfone in CH_2Cl_2 (5 mL) was stirred for 30 min at room temperature. The reaction mixture was evaporated under reduced pressure, and the resulting residue was washed with a small amount of hexane to give 176 mg (98%) of the adduct **7h**: 163.5−164 °C (from CH_2Cl_2/hexane). ^1H NMR: δ 1.32 (s, 9H), 1.40 (s, 9H), 2.20 (dd, J = 13.1, 4.8 Hz, 1H), 2.47 (ddd, J = 13.1, 9.9, 3.8 Hz, 1H), 3.89 (dd, J = 3.8, 2.2 Hz, 1H), 4.20 (ddd, J = 9.9, 4.8, 3.2 Hz, 1H), 4.54 (dd, J = 3.2, 2.2 Hz, 1H), 7.55−7.67 (m, 3H), 7.89−7.92 (m, 2H). ^{13}C NMR: δ 26.5, 31.6, 32.8, 34.2, 35.6, 63.1, 65.6, 66.7, 127.9, 129.4, 133.7, 140.0, 141.1, 143.8. IR: 1307, 1148 (SO_2), 1075 (S═O) cm^{-1}. Anal. Calcd for $C_{20}H_{28}O_3S_2$: C, 63.12; H, 7.42. Found: C, 63.25; H, 7.46.

(i) With *cis*-1,2-Dichloroethylene. A mixture of 100 mg (0.47 mmol) of **1a** and 3 mL of *cis*-1,2-dichloroethylene was heated at reflux for 24 h. The reaction mixture was evaporated under reduced pressure and gave 146 mg (100%) of the adduct **7i**: mp 144−145 °C (from hexane). ^1H NMR: δ 1.32 (s, 18H), 4.38 (dd, J = 1.8, 1.8 Hz, 2H), 5.10 (dd, J = 1.8, 1.8 Hz, 2H). ^{13}C NMR: δ 32.3, 34.2, 56.1, 69.3, 142.1. IR: 1075 (S═O) cm^{-1}. Anal. Calcd for $C_{14}H_{22}Cl_2OS$: C, 54.37; H, 7.17. Found: C, 54.62; H, 7.18.

(j) With Acenaphthylene. A mixture of 42 mg (0.2 mmol) of **1a** and 37 mg (0.24 mmol) of acenaphthylene was heated in boiling toluene (10 mL) for 48 h. The reaction mixture was evaporated under reduced pressure, and the resulting residue was purified by passing it through a short column of silica gel to give 61 mg (84%) of the adduct **7j**: mp 261−262 °C (dec) (from cyclohexane). ^1H NMR: δ 0.86 (s, 18H), 4.46 (dd, J = 2.7, 1.6 Hz, 2H), 4.88 (dd, J = 2.7, 1.6 Hz, 2H), 7.36 (d, J = 7.0 Hz, 2H), 7.46 (dd, J = 8.0, 7.0 Hz, 2H), 7.64 (d, J = 8.0 Hz, 2H). ^{13}C NMR: δ 32.4, 33.8, 48.2, 68.0, 121.2, 123.8, 127.4, 131.3, 141.4, 141.5, 142.1. IR: 1075 (S═O) cm^{-1}. Anal. Calcd for $C_{24}H_{28}OS$: C, 79.07; H, 7.74. Found: C, 78.87; H, 7.75.

(k) With Norbornene. A mixture of 101 mg (0.47 mmol) of **1a** and 52 mg (0.55 mmol) of norbornene was heated in boiling toluene (5 mL). After 4 h, another amount of norbornene (172 mg, 1.8 mmol) was added, and the mixture was heated at reflux for an additional 17 h. The reaction mixture was evaporated under reduced pressure to give 149 mg (96%) of the adduct **7k**: mp 151−152 °C (from CH_2Cl_2/hexane). ^1H NMR: δ 0.85 (s, 1H), 1.25 (s, 18H), 1.25 (m, 2H), 1.55 (m, 2H), 1.73 (m, 1H), 2.29 (m, 2H), 2.57 (m, 2H), 4.00 (m, 2H). ^{13}C NMR: δ 30.1, 31.5, 33.5, 34.5, 37.6, 44.4, 68.4, 139.5. IR: 1080 (S═O) cm^{-1}. Anal. Calcd for $C_{19}H_{30}OS$: C, 74.45; H, 9.87. Found: C, 74.44; H, 10.02.

(l) With Dimethyl Acetylenedicarboxylate (DMAD). A mixture of 107 mg (0.5 mmol) of **1a** and 75 mg (0.5 mmol) of DMAD in CH_2Cl_2 (5 mL) was stirred for 30 min. The reaction mixture was evaporated under reduced pressure, and the resulting residue was chromatographed on a column of silica gel with CH_2Cl_2 as the eluent to give 134 mg (88%) of **8** as colorless liquid, whose spectral data agreed with those of an authentic sample.

Diels−Alder Reactions of Thiophene 1-Imide 3a. (a) With Maleic Anhydride. A mixture of 73 mg (0.2 mmol) of **3a** and 20 mg (0.2 mmol) of maleic anhydride in $CHCl_3$ (10 mL) was heated at reflux for 36 h. The reaction mixture was evaporated, and the resulting residue was washed with a small amount of hexane to give 76 mg (82%) of the adduct **9a**: mp 205−206 °C (from cyclohexane). ^1H NMR: δ 1.28 (s, 18H), 2.43 (s, 3H), 4.38 (dd, J = 2.7, 1.8 Hz, 2H), 4.55 (dd, J = 2.7, 1.8 Hz, 2H), 7.28 (d, J = 8.2 Hz, 2H), 7.73 (d, J = 8.2 Hz). ^{13}C NMR: δ 21.5, 32.3, 35.1, 46.7, 66.0, 125.9, 129.6, 140.7, 142.7, 145.5, 168.3. IR: 2970, 1783, 1270, 1226, 1147, 1091, 1077, 1024, 990, 936 cm^{-1}. Anal. Calcd for $C_{23}H_{29}NO_5S_2$: C, 59.59; H, 6.31; N, 3.02. Found: C, 59.45; H, 6.32; N, 3.01.

(b) With *N*-Phenylmaleimide (NPM). The reaction of 183 mg (0.5 mmol) of **3a** and 90 mg (0.5 mmol) of NPM in $CHCl_3$ (10 mL) for 4 h at reflux gave 249 mg (93%) of the adduct **9b**: mp 212−213 °C (dec) (from EtOH). ^1H NMR: δ 1.29 (s, 18H), 2.42 (s, 3H), 4.25 (dd, J = 2.6, 1.8 Hz, 2H), 4.57 (dd, J = 2.6, 1.8 Hz, 2H), 7.15−7.17 (m, 2H), 7.29 (d, J = 8.3 Hz, 2H), 7.39−7.48 (m, 3H), 7.76 (d, J = 8.3 Hz, 2H). ^{13}C NMR: δ 21.3, 32.3, 34.8, 45.2, 65.6, 125.7, 126.2, 128.9, 129.2, 129.4, 129.6, 131.2, 140.9, 142.2, 144.4, 173.3. Anal. Calcd for $C_{29}H_{34}N_2O_4S_2$: C, 64.66; H, 6.36; N, 5.20. Found: C, 64.58; H, 6.37; N, 5.18.

(c) With Acenaphthylene. The reaction of 73 mg (0.2 mmol) of **3a** and 37 mg (0.24 mmol) of acenaphthylene in boiling $CHCl_3$ (10 mL) for 7 days gave 75 mg (72%) of the adduct **9c**: 208.0−208.5 °C (dec) (from CCl_4). ^1H NMR: δ 0.84 (s, 18H), 2.44 (s, 3H), 4.59 (dd, J = 2.7, 1.6 Hz, 2H), 5.00 (dd, J = 2.7, 1.6 Hz, 2H), 7.30 (d, J = 8.0 Hz, 2H), 7.32 (d, J = 7.0 Hz, 2H), 7.45 (dd, J = 8.6, 7.0 Hz, 2H), 7.65 (d, J = 8.0 Hz, 2H), 7.86 (d, J = 8.6 Hz, 2H). ^{13}C NMR (CD_3CN): δ 21.5, 32.6, 34.9, 49.4, 67.2, 122.0, 125.0, 126.9, 128.6, 128.7,

130.5, 131.2, 132.4, 141.7, 143.6, 144.7. Anal. Calcd for $C_{31}H_{35}NO_2S_2$: C, 71.91; H, 6.81; N, 2.71. Found: C, 71.77; H, 6.81; N, 2.65.

(d) With Dimethyl Acetylenedicarboxylate (DMAD). A mixture of 183 mg (0.5 mmol) of **3a** and 74 mg (0.5 mmol) of DMAD in $CHCl_3$ (10 mL) was heated at reflux for 5 days. The reaction mixture was evaporated under reduced pressure, and the resulting residue was chromatographed on a column of silica gel with CH_2Cl_2 as the eluent to give 80 mg (52%) of **8** as a colorless liquid, whose spectral data agreed with those of an authentic sample.[11]

Reaction of Thiophene 1-Imide 3a with *N*-Phenyl-1,3,5-triazoline-2,4-dione (PTAD); Formation of the Thiazetidine 12a. A mixture of 92 mg (0.25 mmol) of **3a** and 87 mg (0.50 mmol) of PTAD in CH_2Cl_2 (5 mL) was heated at reflux for 10 h. The reaction mixture was evaporated, and the resulting residue was chromatographed on a short column of Florisil with CH_2Cl_2 as the eluent to give 109 mg (81%) of the adduct **12a**. The reaction at room temperature for 7 days gave **12a** in 65% yield. **12a**: mp 153−158 °C (dec) (from Et_2O). ^{1}H NMR: δ 0.77 (s, 9H), 1.39 (s, 9H), 2.48 (s, 3H), 5.81 (s, 1H), 7.26−7.27 (m, 1H), 7.40−7.53 (m, 4H), 7.45 (d, J = 8.0 Hz, 3H), 7.52 (s, 1H), 8.08 (d, J = 8.0 Hz, 2H). ^{13}C NMR: δ 21.7, 28.7, 33.8, 37.0, 38.0, 64.5, 69.2, 115.7, 124.4, 125.9, 127.7, 128.7, 129.3, 129.5, 130.5, 130.8, 144.3, 145.4, 146.0. Anal. Calcd for $C_{27}H_{32}N_4O_4S_2$: C, 59.97; H, 5.97; N, 10.36. Found: C, 59.93; H, 5.83; N, 10.26.

Reaction of Thiophene 1-Imide 3b with *N*-Phenyl-1,3,5-triazoline-2,4-dione (PTAD); Formation of the Tricyclic Compound 17. A mixture of 128 mg (0.5 mmol) of **3a** and 132 mg (0.8 mmol) of PTAD in CH_2Cl_2 (10 mL) was stirred at reflux for 7 days at room temperature. The reaction mixture was evaporated, and the resulting residue was chromatographed on a short column of silica gel with CH_2Cl_2 as the eluent to give 129 mg (60%) of the tricyclic compound **17**: mp 144−146 °C (from Et_2O/hexane). ^{1}H NMR: δ 1.16 (s, 9H), 1.35 (s, 9H), 2.00 (s, 3H), 6.05 (s, 1H), 7.08 (s, 1H), 7.40−7.44 (m, 1H), 7.47−7.57 (m, 4H). ^{13}C NMR: δ 21.7, 27.6, 32.2, 36.8, 39.4, 55.3, 77.0, 114.9, 125.6, 126.3, 128.6, 129.3, 130.7, 145.3, 149.3, 154.8. Anal. Calcd for $C_{22}H_{28}N_4O_3S$: C, 61.66; H, 6.59; N, 13.07. Found: C, 61.89; H, 6.61; N, 13.11.

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Supporting Information Available: X-ray crystallographic data of **3a**, **7a**,**b**,**k**, **9a**, **12a**, and **17** and programs used for visualizing the orbitals and pdb-files of the optimized structures in the computational study (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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