lowship to H.R.G. and to Dr. Catherine Costello for high-resolution mass spectra.

Registry No. 2, 74763-43-2; 7, 71516-83-1; 8, 55183-44-3; 9, 37794-60-8; 10, 74763-44-3; 11, 74763-45-4; 12, 74763-46-5; 13, 74763-47-6; 14, 74763-48-7; 15, 74763-49-8; 16, 74806-92-1; 17, 74763-50-1; 18, 74763-51-2; 19, 74763-52-3; 20, 74806-93-2; 21, 74806-94-3; 22, 74806-95-4; 23, 74763-53-4; 24, 74763-54-5; 25, 74763-55-6; imidazole, 288-32-4; methyltriphenylphosphonium bromide, 1779-49-3; 4-methylpent-2(*E*)-enal, 24502-08-7; 2-methoxy-1,3-dioxane, 17230-31-8; 1,3-propanediol, 504-63-2; methyl chloroformate, 79-22-1; ethylene glycol, 107-21-1.

Regio- and Stereoselectivity in the Ene Reaction of *N*-Phenyl-1,2,4-triazoline-3,5-dione with α,β-Unsaturated Carbonyl Substrates

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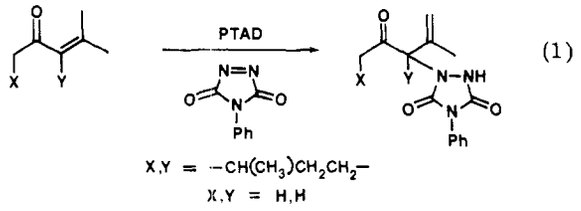
N-Phenyltriazoline-3,5-dione reacts with α,β-unsaturated ketones, esters, and lactones **1a–l** to give ene adducts **2a–l**. The reactions usually proceed in good yield with high regioselectivity and, where possible, high stereoselectivity. Ene substrates capable of adopting an s-cis conformation show much greater reactivity. A variety of mechanistic interpretations is considered.

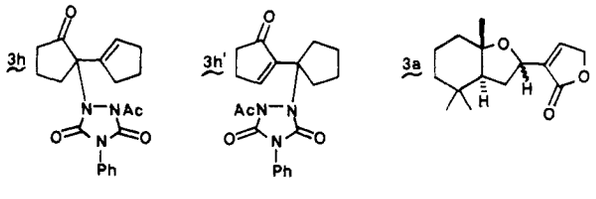
The ene reaction between an olefin bearing an allylic hydrogen atom (ene) and a multiple π bond (enophile) is a well-documented[2a] and powerful[2b,c] transformation. In the vast majority of these reactions the olefinic ene partner is an electron-rich double bond. In the course of another synthetic study we encountered a need to allylically functionalize compound **1a** and observed its efficient transformation into **2a** (see entry 1, Table I) upon exposure to *N*-phenyl-1,2,4-triazoline-3,5-dione (PTAD). This result was somewhat surprising in view of the reported[3] mode of reaction of PTAD with pulegone and mesityl oxide (eq 1), since each of these substrates gave rise to β,γ-unsaturated carbonyl products whereas **1a** led specifically to the allylically transposed α,β-unsaturated lactone **2a**. We therefore investigated the reaction of PTAD with a variety of α,β-unsaturated carbonyl substrates in an attempt to define the structural parameters responsible for these differences in reactivity. In contrast to the voluminous literature on singlet oxygen ene selectivity with unsymmetrical electron-rich olefins,[4] a recent communication by Magnus and co-workers[5a] and reports by Butler et al.[5b] appear to be the only reports of similar studies with PTAD as the enophile. Herein we report the results of our study of the reaction between electron-deficient olefins (i.e., carbonyl-substituted olefins) and PTAD.



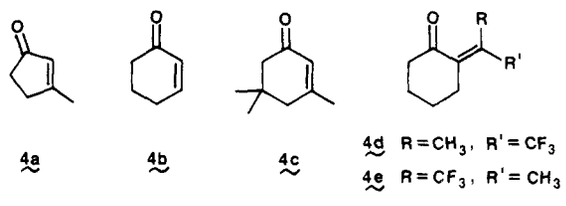
(1)

Results

In Table I are listed the α,β-unsaturated carbonyl ene substrates **1a–l** which were allowed to react with PTAD (1.0 equiv) at room temperature in methylene chloride (CH_2Cl_2) or deuteriochloroform ($CDCl_3$). The substrates were converted with high regioselectivity (with the exception of **1h**) and, where detectable (entries 12, 13), high stereoselectivity to the ene adducts **2a–l** in good yields. While some of these adducts were crystalline, others were amorphous solids or oils, and all behaved poorly when subjected to silica gel chromatography. Thus, it was in general difficult to assay for minor regio- and stereoisomeric products beyond the limits of ^1H NMR analysis of the crude reaction mixtures (5–10% detection limits, depending upon product structure). Late in the study it was discovered that the ene adducts **2** could be acetylated at the free NH group. The crude products **2h** and **2h′** were derivatized in this manner, and the resulting acetamides **3h** and **3h′** could be readily separated chromatographically. In a similar attempt to acetylate and separate the epimeric ene adducts **2a**, we observed a facile base-induced ring closure to the epimeric tetrahydrofurans **3a**. Further synthetic aspects of this cyclization will be discussed elsewhere.



Enones **4a–e** did not react with PTAD at room temperature in $CDCl_3$ even after several days. Product ene adducts containing both a β,γ-enone moiety and an α-hydrogen atom (i.e., **2b** and **2c**) underwent partial isom-



(1) (a) Lando Fellow, University of Minnesota, Summer 1978. (b) Dissertation Fellow, University of Minnesota, 1980–81.
(2) (a) Hoffman, H. M. R. *Angew. Chem., Int. Ed. Engl.* **1969**, *8*, 566. (b) Conia, J. M.; LePerchec, P. *Synthesis* **1975**, 1. (c) Oppolzer, W.; Snieckus, V. *Angew. Chem., Int. Ed. Engl.* **1978**, *17*, 476.
(3) Shiloff, J. D.; Hunter, N. R *Tetrahedron Lett.* **1976**, 3773. We thank Professor Hunter for an exchange of information regarding his further study of this reaction.
(4) Denny, R. W.; Nickon, A. *Org. React.* **1973**, *20*, Chapter 2.
(5) (a) Gopalan, A.; Moerck, R.; Magnus, P. *J. Chem. Soc., Chem. Commun.* **1979**, 548. (b) Ohashi, S.; Leong, K.; Matyjaszewski, K.; Butler, G. B. *J. Org. Chem.* **1980**, *45*, 3467; Ohashi, S.; Butler, G. B. *Ibid.* **1980**, *45*, 3472.

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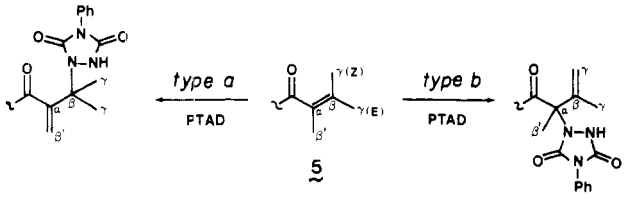
Table I. Reaction of α,β-Unsaturated Carbonyl Substrates 1 with PTAD To Give Adducts 2

entry	substrate	adduct[a]	% yield[b]	entry	substrate	adduct[a]	% yield[b]
1	1a	2a	94	8	1g(Z)	2g	90
2	1b	2b	95	9	1g(E)		
3	1c	2c	65	10	1h	2h + 2h' (5:4)	94
4	1d	2d	94	11	1i	2i[c]	84
5	1e	2e	72	12	1j	2j	—
6	1f(Z)	2f	77	13	1k	2k[d]	—
7	1f(E)			14	1l	2l	91

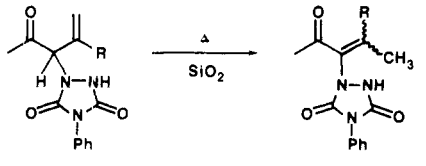
[a] The circle on N represents the 3,5-dioxo-4-phenyl-1,2,4-triazolidino moiety (PTADH) throughout. [b] Yields refer to purified adducts of greater than 95% purity. [c] A mixture of epimers. [d] It was not possible to determine whether both stereoisomers or only one of 2k was formed.

Scheme I



5

erization to the conjugated enones **3b** and **3c**, respectively, upon recrystallization. In the latter case, this process could be driven to completion by refluxing the nonconjugated adduct in benzene in the presence of silica gel (eq 2).



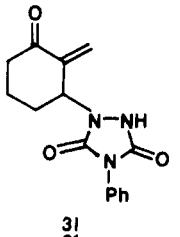
(2)

2b R = H
2c R = CH3

3b R = H
3c R = CH3

Discussion

The reaction of PTAD with ene substrates 1 shows a strong preference for enones capable of adopting an s-cis conformation. This is possible for every entry in Table I except the last (entry 14), whereas substrates **4a–c**, which are confined to be s-trans, are unreactive. The only exception to this preference is 2-methyl-2-cyclohexenone (**1l**), and even in that instance the intitial adduct (presumably **3l**) was not observed since it reacted with a second



3l

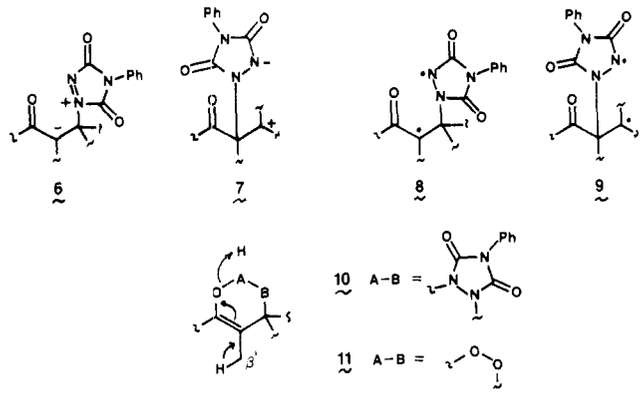
equivalent of PTAD to give the 2:1 adduct **2l** at a rate faster than that of its formation. The s-cis structural requirement was noted earlier by Hunter and Shiloff[3] and is also necessary for successful net ene reactions of enones with singlet oxygen.[6]

(6) Ensley, H. E.; Carr, R. V. C. *Tetrahedron Lett.* **1977**, 513. Ensley, H. E.; Carr, R. V. C.; Martin, R. S.; Pierce, T. E. *J. Am. Chem. Soc.* **1980**, *102*, 2836.

Regiochemistry. For the purpose of further discussion it will be useful to refer to carbon atoms α, β, β', $\gamma(Z)$, and $\gamma(E)$ of the substrate olefin as defined in structure **5** of Scheme I. The regiochemistry of the reaction of **5** with PTAD can then be categorized as a type a or type b process as shown in the Scheme I. In pathway a the nitrogen atom of the enophile has become bonded to C_β, and the β'-allylic hydrogen has been transferred, whereas a new C_α–N bond and transfer of one of the γ-allylic hydrogens result from pathway b. Substrates **1b–d** (entries 2–4) can each only afford a single product. The first two proceed via a type b and the last by a type a reaction pathway. Both occur; thus both reaction modes are, a priori, feasible. All of the remaining substrates in Table I contain both β'-allylic hydrogen atoms and at least one type of γ-allylic hydrogen atom and therefore have both type a and type b reaction pathways available to them. Those substrates which bear only one alkyl substituent on the β-carbon (**1a**, **1e**, **1f**(Z), **1f**(E), **1g**(Z), **1g**(E), and **1l**), regardless of whether the C_γ is cis or trans to the carbonyl group, always give the α,β'-unsaturated product arising from a type a ene reaction (entries 1, 5–9, and 14). Alternatively, substrates which bear two alkyl substituents on the β-carbon (**1i–k**) provide the β,γ-unsaturated products which arise from a type b reaction mode. The lone exception to this trend is substrate **1h** which leads to a mixture of type a and b products **2h′** and **2h**, respectively.

Stereochemistry. It is obviously not possible to determine if there is a preference for abstraction of a $\gamma(Z)$- vs. a $\gamma(E)$-allylic hydrogen in the type b reaction of PTAD with substrates **1c**, **1h**, and **1i** since either event would provide the same product (entries 3, 10, and 11). Therefore, (E)- and (Z)-2-(1-methylpropylidene)cyclohexanone (**1j** and **1k**) were prepared in order to probe the stereoselectivity of the type b reaction. Within the limits of detection each of these olefins was stereospecifically transformed to that product arising from preferential transfer of the $\gamma(Z)$-allylic hydrogen (entries 12 and 13) even though those hydrogens were primary in the former and secondary in the latter case.

Mechanism. Numerous mechanistic pictures of the above results can be considered. Reasonable stepwise mechanisms might involve dipolar species of type **6** and **7**, diradical intermediates such as **8** and **9**, or neutral cycloadducts of structure **10**. Type a product formation would arise through transfer of the β'-hydrogen atom to the more remote nitrogen atom in intermediates **6** and **8** or via collapse of **10** as shown by the arrows. The value of invoking dipole **6** vs. **7** or diradical **8** vs. **9** lies in their ability to account reasonably well for the observed regiochemical dependence of the reaction on enone substitution patterns. Thus, it is intuitive that placing more alkyl substituents on C_β should increase the relative importance of dipole **7** vs. **6** or diradical **9** vs. **8**, thereby increasing the propensity for a type b reaction. Whether this perturbation would be of sufficient magnitude to account entirely for the observed regioselectivity is debatable.



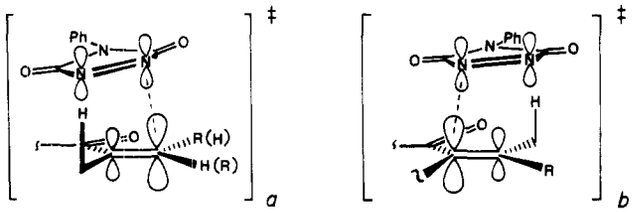
There are several points which are less consistent with the stepwise mechanisms. If either **6** or **8** is involved, it is difficult to rationalize the greatly diminished reactivity of the s-trans enones, since these intermediates should be readily accessible from the s-trans enones. The formal Diels–Alder adduct **10** is analogous to intermediate **11** which has been suggested to intervene in the previously mentioned reaction of s-cis enones with singlet oxygen.[6] However, type b products cannot easily be rationalized via the intermediacy of **10**. Moreover, the reaction of the s-trans enone **1l** (entry 14), albeit sluggish, is inconsistent with the cycloadduct **10**. Therefore, if such a species is involved, type a and type b products must arise via competing mechanistic pathways. Returning to the possibility of type b products arising through dipolar or diradical intermediates **7** or **9**, we recognize that collapse of each to product through transfer of the $\gamma(Z)$-hydrogen atom would have to be faster than rotation about the C_α–C_β bond in order to account for the stereoselectivity observed in the reaction of olefin isomers **1j** and **1k** (entries 12 and 13). In addition, the sole formation of unconjugated enones **2b** and **2c** from 3-penten-2-one (**1b**) and mesityl oxide (**1c**), respectively (entries 2 and 3), argues against intermediates **7** and **9**, since, had these species been involved, one might expect to have seen some leakage of **7** or **9** to the thermodynamically favored enone **3b** or **3c** (vide infra, eq 2) by transfer of the α-hydrogen present in both substrates **1b** and **1c**.

A concerted reaction mechanism which proceeds through a transition state that involves both partial carbon–nitrogen bond formation and allylic hydrogen atom transfer can also be considered. These two events need not be advanced to the same degree, of course, and the transition states for the type a and b pathways can therefore be thought of as having some of the structural characteristics of the dipolar and/or diradical depictions **6**/**8** and **7**/**9**, respectively. The intuitive argument previously presented relating regiochemistry to enone substitution pattern in a stepwise mechanism could be translated directly to the relative transition-state energies for a concerted process.

Qualitative frontier molecular orbital analysis perhaps provides a more comprehensive rationalization of the data. The lack of reactivity of both (E)- and (Z)-trifluoromethyl-substituted enones **4d** and **4e**—the only s-cis substrates which did not react—is consistent with a dominant interaction of the ene HOMO with the enophile (PTAD) LUMO. The trifluoromethyl group should lower the ene HOMO energy relative to, say, pulegone (**1i**), thereby increasing $\Delta E_{\text{LUMO-HOMO}}$ and diminishing the reaction rate.[7] The regioselectivity (i.e., type a vs. type b competition) could be a reflection of the relative magnitude of HOMO coefficients at C_α and C_β in the enone.

Transition state representations **12** and **13** indicate an "endo" approach of PTAD to the s-cis enone conformation. This geometry might be expected to prevail on the basis of a secondary orbital interaction between the PTAD imidic O=C—N unit and the enone carbonyl group. Preferential endo addition accounts for the stereospecific transfer of the $\gamma(Z)$-allylic hydrogen in the type b reaction of E and Z isomers **1j** and **1k**. It is also consistent with the observation that **1f**(E) undergoes the type a reaction

(7) Attempts to correlate relative reaction rates to the degree of enone alkyl substitution by analysis of the results of direct competition experiments of several sets of ene substrates **1** were complicated by a layering of steric effects onto the assumed changes in HOMO energy.



12 13

at a faster rate (direct competition) than does **1f**(*Z*). In this case the methyl substituent cis to the carbonyl in **1f**(*Z*) would impose a greater steric barrier to attainment of the endo transition state **12** than would the trans methyl group in **1f**(*E*).

Finally, it is conceivable that the reaction mechanism involves prior electron transfer from the olefin to PTAD followed by coupling of the resultant radical cation and radical anion. However, the frontier molecular orbital analysis would remain essentailly unchanged since SOMO–SOMO interaction would dominate transition-state energies, and this is equivalent to HOMO–LUMO overlap for the two neutral reaction partners.

Experimental Section

General Methods. Melting points were determined on a Kofler hot stage and are uncorrected. Elemental analyses were performed by M-H-W Laboratories. Infrared spectra were recorded on a Perkin-Elmer 237 instrument, proton nuclear magnetic resonance spectra obtained on a Varian HFT-80 instrument in the Fourier transform mode, and mass spectra were determined on AE1 MS-30 [electron impact (EI), 70 eV] and Finnigan 4000 (chemical ionization, CI) instruments.

Source of Substrates 1. Compounds **1b–e,h,i** and **4a–c** are commercially available. Preparation of compound **1a** will be described by us in a future publication. Isomers **1f**(*Z*)/**1f**(*E*),[8a] **1g**(*Z*)/**1g**(*E*),[8b] **1j**/**1k**,[8c] and compound **1l** were prepared by literature procedures. Careful separation of **1j** and **1k** by preparative gas chromatography (12 ft × $^1/_4$ in. column, 10% FFAP, 140 °C) gave milligram quantities of the pure isomers. **1j**: ^{1}H NMR ($CDCl_3$) δ 0.99 (t, J = 7 Hz, 3 H, CH_3CH_2), 1.92 (t, J = 2 Hz, 3 H, $CH_3C{=}C$), 2.09 (q, J = 7 Hz, 2 H, CH_2CH_3). **1k**: ^{1}H NMR ($CDCl_3$) δ 1.02 (t, J = 7 Hz, 3 H, CH_3CH_2), 1.71 (t, J = 1 Hz, 3 H, $CH_3C{=}C$), 2.27 (br q, J = 7 Hz, 2 H, CH_2CH_3). Isomers **4d** and **4e** were prepared by the method of Mukaiyama.[8c] 1-(Trimethylsiloxy)cyclohexene and 1,1,1-trifluoroacetone gave a 90% crude yield of a 2:1 mixture of diastereomeric aldol products. These could be separated by preparative gas chromatography (8 ft × $^1/_4$ in. column, 5% DEGS, 130 °C) to give each pure diastereomer of 2-(1-hydroxy-1-methyl-2,2,2-trifluoroethyl)cyclohexanone. Major isomer: ^{1}H NMR ($CDCl_3$) δ 1.36 (q, J = 1 Hz, 3 H, CH_3), 1.5–2.0 (m, 8 H), 2.83 (dd, J = 6, 11 Hz, 1 H, COCH), 5.23 (s, 1 H, OH). Minor isomer: ^{1}H NMR ($CDCl_3$) δ 1.43 (q, J = 1 Hz, 3 H, CH_3), 1.5–2.8 (m, 9 H), 5.05 (s, 1 H, OH). This aldol mixture could be dehydrated, although inefficiently due to isomerization of **4d** and **4e** to a β,γ-enone and polymerization, by being refluxed in benzene in the presence of *p*-toluenesulfonic acid. Purification by short-column chromatography[9] on silica gel (12:1 hexanes–EtOAc) gave **4d** (8%), β,γ-enone (3%), and **4e** (5%). **4d**: ^{1}H NMR ($CDCl_3$) δ 1.89 (t, J = 1 Hz, 3 H, CH_3), 1.6–2.1 (m, 4 H), 2.50 (t, J = 7 Hz, 2 H, CH_2CO), 2.65 (m, 2 H, $CH_2C{=}C$); IR (neat) 2940, 2860, 1710, 1660, 1450, 1320, 1250, 1170, 1120, 1100, 1070 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 192 (1), 164 (4), 149 (1), 132 (3), 122 (3), 104 (3), 95 (3), 44 (100). β,γ-enone: ^{1}H NMR ($CDCl_3$) δ 1.5–2.6 (m, 6 H), 3.25 (m, 1 H, COCH), 5.45 (br s, 1 H, $H_{cis}C{=}CCF_3$), 5.98 (q, J = 2 Hz, 1 H, $H_{trans}C{=}CCF_3$); IR (neat) 2940, 2860, 1715, 1650, 1445, 1420, 1330, 1295, 1165, 1110 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 192 (35), 172 (6), 164 (16), 163 (22), 148 (36), 122 (66), 95 (52), 79 (100). Anal. Calcd for $C_9H_{11}F_3O$: *m/e* 192.0761. Found: *m/e* 192.0752. **4e**: ^{1}H NMR ($CDCl_3$) δ 1.85 (s, 3 H, CH_3), 1.7–2.2 (m, 4 H), 2.55 (m, 4 H); IR (neat) 2940, 2860, 1705, 1650, 1445, 1310, 1275, 1250, 1220, 1165, 1120, 1025 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 192 (57), 172 (11), 164 (9), 144 (38), 136 (15), 115 (16), 95 (26), 67 (100). Anal. Calcd for $C_9H_{11}F_3O$: *m/e* 192.0761; C, 56.25; H, 5.77. Found: *m/e* 192.0756; C, 55.85; H, 5.98.

General Procedure for Reaction of Substrates 1 with PTAD. A solution of substrate 1 in methylene chloride (0.1–0.3 M) was rapidly added to 1.0 equiv of a stirred solution of PTAD[10] in CH_2Cl_2 (0.1–0.3 M) at room temperature. When the red color of the PTAD had dissipated (10 min to 1 day) the resulting mixture, usually a suspension of a slight amount of white precipitate in a yellow solution, was filtered through a cotton plug and concentrated to leave the crude product. In all cases, ^{1}H NMR analysis suggested the crude products were >90% pure. Purification, yield, and physical and spectral properties for products **2** follow.

3-[2-[2(*RS*)-Hydroxy-2,6,6-trimethyl-1(*RS*)-cyclohexyl]-1(*RS*)- and -1(*SR*)-(4-oxa-5-oxocyclopentenyl)-ethyl]-4-phenyl-1,2,4-triazolidine-3,5-diones (2a). Addition of 3 volumes of 1:1 hexanes–EtOAc to the filtered reaction mixture in methylene chlorine caused a powdery, more polar diastereomer to precipitate (32% crude yield). The supernatant contained 62% of a crude less polar diastereomer. More polar isomer: ^{1}H NMR (py-d_5) δ 0.91, 1.22, 1.34 (3 s, 3 H, CH_3's), 1.5–2.4 (br m, 9 H), 4.72 (br s, 2 H, CH_2O), 5.54 (br t, J = 7 Hz, 1 H, CHN), 7.2–7.8 (br m, 6 H); IR (KBr) 3460, 3050, 2930, 1765, 1705, 1655, 1600, 1500, 1430, 1060 cm^{-1}; mass spectrum (CI, NH_3, positive ion), *m/e* 445 (M + NH_4), 427 (M + NH_4^+ – H_2O), 268 (base, M + NH_4^+ – $PTADH_2$), (NH_3, negative ion) 426 (M – H^+), 176 (base, $PTAD^-$). Less polar isomer: ^{1}H NMR ($CDCl_3$) δ 0.78, 0.96, 1.22 (3 s, 3 H, CH_3's), 1.0–2.4 (br m, 9 H), 4.82 (br s, 2 H, CH_2O), 5.70 (dd, J = 10, 5 Hz, 1 H, CHN), 7.4 (br s, 6 H); IR ($CHCl_3$) 3250, 2930, 1760, 1740, 1705, 1600, 1500, 1420 cm^{-1}; mass spectrum (CI, NH_3, positive ion), 445, 428 (M + H^+), 427, 268, (NH_3, negative ion) 426, 176. Attempted acetylation (Ac_2O, Et_3N, CH_2Cl_2) led to conversion of crude **2a** to the cyclic ethers **3a**. These have been completely characterized in connection with another study and details will soon be reported.

1-(1-Acetyl-2-propenyl)-4-phenyl-1,2,4-triazolidine-3,5-dione (2b). Precipitation of an ethyl acetate solution of crude **2b** with hexanes provided an amorphous solid in 95% yield: ^{1}H NMR ($CDCl_3$) δ 2.23 (s, 3 H, CH_3), 5.35 (d, J = 8 Hz, 1 H, NCH), 5.54 (d, J = 8 Hz, 1 H, CH=CHH), 5.54 (d, J = 16 Hz, 1 H, CH=CHH), 5.96 (ddd, J = 16, 8, 8 Hz, 1 H, CH=CH_2), 7.4 (br s, 5 H, Ph); IR (CH_2Cl_2) 3345, 1785, 1715, 1605, 1505, 1415, 1250, 895 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 259 (9), 216 (19), 119 (55), 43 (100). Anal. Calcd for $C_{13}H_{13}N_3O_3$: *m/e* 259.0955. Found: *m/e* 259.0937. Attempted chromatography on silica gel led to partial isomerization of **2b** to **3b**.

1-(1-Acetyl-2-methyl-2-propenyl)-4-phenyl-1,2,4-triazolidine-3,5-dione (2c). Crude **2c** was dissolved in EtOAc and precipitated with hexanes to give a 65% yield of off-white crystalline **2c**. Recrystallization from hexanes–EtOAc gave an analytical sample: mp 126–133 °C; ^{1}H NMR ($CDCl_3$) δ 1.87 (dd, J = 2, 1 Hz, 3 H, $CH_3C{=}C$), 2.25 (s, 3 H, CH_3CO), 5.02 (br s, 1 H, HHC=C), 5.23 (q, J = 2 Hz, 1 H, HHC=C), 5.37 (s, 1 H, CHN), 7.4 (br s, 5 H, Ph); IR (KBr) 3130, 1775, 1720, 1690, 1495, 1445, 1140, 930, 780, 745, 680 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 273 (16), 230 (98), 119 (82), 118 (74), 111 (100), 93 (23), 91 (36), 83 (42), 77 (73), 68 (91), 43 (91), 43 (91). Anal. Calcd for $C_{14}H_{15}N_3O_3$: C, 61.53; H, 5.53; N, 15.48. Found: C, 61.42; H, 5.33; N, 15.34. Extensive heating of **2c** during recrystallization or heating neat **2c** (i.e., during the melting point determination) led to varying amounts of isomerization to **3c** (vide supra).

1-[2-(Methoxycarbonyl)-2-propenyl]-4-phenyl-1,2,4-triazolidine-3,5-dione (2d). Precipitation of an ethyl acetate solution of crude **2d** with hexanes provided an amorphous solid in 94%

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(10) In our hands the preparation of PTAD by nitrogen tetroxide oxidation (Stickler, J. C.; Pirkle, W. H. *J. Org. Chem.* **1966**, *31*, 3444) proved to be more efficient and was easier to perform than the *tert*-butyl hypochlorite method (Cookson, R. C.; Gupte, S. S.; Stevens, I. D. R.; Watts, C. T. *Org. Synth.* **1971**, *51*, 121).

yield: ^{1}H NMR ($CDCl_3$) δ 3.74 (s, 3 H, OCH_3), 4.37 (br s, 2 H, CH_2N), 5.88 (br s, 1 H, C=CHH), 6.33 (br, s, 1 H, C=H-H), 7.4 (br s, 5 H, Ph); IR ($CHCl_3$) 3350, 1780, 1710, 1640, 1605, 1505, 1440 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 275 (58), 243 (100), 119 (56), 68 (44). Anal. Calcd for $C_{13}H_{13}N_3O_4$: *m/e* 275.0906. Found: *m/e* 275.0925.

1-(2-Acetyl-2-cyclohexenyl)-4-phenyl-1,2,4-triazolidine-3,5-dione (2e). The crude solid (98% mass yield) was recrystallized from EtOAc–EtOH to give a 72% yield of analytically pure **2e**: mp 179–181 °C; ^{1}H NMR ($CDCl_3$) δ 1.6–2.2 (m, 6 H), 2.25 (s, 3 H, $COCH_3$), 5.05 (br m, 1 H, CHN), 7.09 (br t, J = 4 Hz, 1 H, C=CH), 7.3–7.5 (m, 5 H, Ph); IR (KBr) 3100, 1770, 1710, 1670, 1605, 1500, 1440, 1270, 1250, 1040, 890, 860, 770, 720, 660 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 299 (2), 177 (19), 123 (62), 119 (28), 79 (22), 77 (23), 43 (100). Anal. Calcd for $C_{16}H_{17}N_3O_3$: C, 64.20; H, 14.04; N, 5.72. Found: C, 64.20; H, 14.09; N, 5.76.

1-[1-(6-Oxo-1-cyclohexenyl)ethyl]-4-phenyl-1,2,4-triazolidine-3,5-dione (2f). The crude product was recrystallized once from hexanes–EtOAc–EtOH to give a 77% yield of crystalline **2f**. Four additonal recrystallizations from EtOAc–EtOH gave an analytical sample: mp 147–151 °C; ^{1}H NMR ($CDCl_3$) δ 1.48 (d, J = 7 Hz, 3 H, CH_3), 2.0 (m, 2 H), 2.4 (m, 4 H), 4.91 (br q, J = 7 Hz, 1 H, CHN), 7.05 (br t, J = 4 Hz, 1 H, CH=C), 7.4 (br s, 5 H, Ph); IR (KBr) 3150, 3050, 1765, 1710, 1700, 1680, 1605, 1505, 1430, 1390, 1260, 775, 700, 650 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 299 (17), 177 (15), 123 (100), 119 (21). Anal. Calcd for $C_{16}H_{17}N_3O_3$: C, 64.20; H, 5.72; N, 14.04. Found: C, 63.81; H, 5.91; N, 14.15.

1-[1-(4-Oxa-5-oxocyclopentenyl)ethyl]-4-phenyl-1,2,4-triazolidine-3,5-dione (2g). The crystalline product precipitated from CH_2Cl_2 and was filtered and washed with CH_2Cl_2 to give **2g** in 90% yield. Four recrystallizations from acetonitrile gave an analytical sample: mp 209–211 °C; ^{1}H NMR ($CDCl_3$) δ 1.60 (d, J = 7 Hz, 3 H, CH_3), 4.89 (d, J = 2 Hz, 2 H, CH_2O), 5.36 (br q, J = 7 Hz, 1 H, CHN), 7.3–7.5 (m, 6 H, Ph, CH=C); IR (KBr) 3170, 1785, 1750, 1705, 1600, 1500, 1450, 780, 700 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 287 (8), 177 (96), 120 (46), 119 (100), 111 (38), 110 (58), 91 (29), 77 (49), 53 (67), 44 (79). Anal. Calcd for $C_{14}H_{13}N_3O_4$: C, 58.53; H, 4.56; N, 14.62. Found: C, 58.27; H, 4.40; N, 14.80.

1-[1-(1-Cyclopentenyl)-2-oxocyclopentyl]-4-phenyl-1,2,4-triazolidine-3,5-dione (2h) and 1-[1-(5-Oxo-1-cyclopentenyl)cyclopentyl]-4-phenyl-1,2,4-triazolidine-3,5-dione (2h'). The crude product was slurried in hexanes–EtOAc, filtered, and dried to give a mixture of crystalline **2h** and **2h'** in 94% yield. Three recrystallizations from CH_3CN and one from benzene gave an analytical sample of **2h**: mp 189–191 °C; ^{1}H NMR ($CDCl_3$) δ 1.6–3.0 (m, 12 H), 5.71 (br s, 1 H, HC=C), 7.4 (br s, 5 H, Ph), 8.15 (br s, 1 H, NH); IR (KBr) 3150, 1765, 1755, 1690, 1595, 1495, 1440, 1150, 810, 770, 700, 650 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 325 (2), 177 (7), 149 (100). Anal. Calcd for $C_{18}H_{19}N_3O_3$: C, 66.45; H, 5.89; N, 12.92. Found: C, 66.69; H, 5.92; N, 12.97. Compounds **2h** and **2h'** were further characterized as their acetyl derivatives **3h** and **3h'**.

1-[4(*R*)-Methyl-1(*R*)- and -1(*S*)-(1-methylethenyl)-2-oxocyclohexyl]-4-phenyl-1,2,4-triazolidine-3,5-dione (2i).[3] The crude product was slurried in hexanes–EtOAc and filtered to provide crystalline **2i** in 84% yield. Recrystallization (4×) from benzene gave an analytical sample of the epimeric mixture **2i**: mp 178–181 °C; ^{1}H NMR ($CDCl_3$) δ 1.01 and 1.02 (2 d, J = 7 Hz, CH_3CH), 1.82 (dd, J = 2, 1 Hz, CH_3C=C), 1.87 (dd, J = 2, 1 Hz, CH_3C=C), 4.99 (br s, HHC=C), 5.08 (br s, HHC=C), 5.28 (br q, J = 2 Hz, HHC=C), 5.36 (br q, J = 2 Hz, HHC=C), 7.4 (br s, Ph); IR (KBr) 3200, 3100, 1775, 1710, 1605, 1510, 1440, 1140, 775, 715, 690 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 327 (1), 177 (3), 151 (54), 123 (22), 81 (32), 44 (100). Anal. Calcd for $C_{18}H_{21}N_3O_3$: C, 66.04; H, 6.47; N, 12.84. Found: C, 66.27; H, 6.26; N, 12.89.

1-[1-(1-Ethylethenyl)-2-oxocyclohexyl]-4-phenyl-1,2,4-triazolidine-3,5-dione (2j). The reaction was performed on approximately 3 mg of pure *E* enone **1j**. Recrystallization of the crude product from benzene–hexanes gave crystalline **2j**: mp 199–204 °C; NMR ($CDCl_3$) δ 1.13 (t, J = 7 Hz, 3 H, CH_3CH_2), 1.6–3.1 (m, 10 H), 5.24 (br s, 1 H, HHC=C), 5.43 (br t, J = 1 Hz, 1 H, HHC=C), 7.4 (br s, 5 H, Ph), 8.1 (br s, 1 H, NH); IR ($CDCl_3$) 3340, 1770, 1700, 1600, 1500, 1420, 1260, 1125, 1025 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 327 (10), 177 (29), 151 (100), 123 (25), 122 (37), 81 (55). Anal. Calcd for $C_{18}H_{21}N_3O_3$: *m/e* 327.1579. Found: *m/e* 327.1582.

(*E*)- and/or (*Z*)-1-[1-(1-Methyl-1-propenyl)-2-oxocyclohexyl]-4-phenyl-1,2,4-triazolidine-3,5-dione (2k). This reaction was performed on approximately 2 mg of pure *Z* enone **1k**. Recrystallization of the crude adduct from benzene–hexanes gave crystalline **2k**: mp 210–212 °C; NMR ($CDCl_3$) δ 1.65 (br m, 6 H, 2 CH_3's), 1.8–3.1 (m, 8 H), 5.7 (br m, 1 H, HC=C), 7.4 (br s, 5 H, Ph); IR ($CDCl_3$) 3340, 1770, 1705, 1600, 1500, 1440, 1260, 1025 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 327 (7), 177 (17), 151 (100), 81 (29). Anal. Calcd for $C_{18}H_{21}N_3O_3$: *m/e* 327.1579. Found: *m/e* 327.1586.

1-[3-Oxo-2-(3,5-dioxo-4-phenyl-1,2,4-triazolidinomethyl)-1-cyclohexenyl]-4-phenyl-1,2,4-triazolidine-3,5-dione (2l). Crude **2l** which precipitated from the CH_2Cl_2 reaction mixture was washed with hexanes to give a 91% yield of diadduct **2l** as an amorphous foam: ^{1}H NMR (Me_2SO-d_6) δ 2.05 (m, 2 H, $COCH_2CH_2$), 2.40 (m, 2 H), 2.80 (m, 2 H), 4.59 (br s, 2 H, CH_2N), 7.4–7.5 (br s, 10 H, Ar H); IR (KBr) 3070, 1775, 1715, 1655, 1610, 1600, 1500, 1420, 1300, cm^{-1}; mass spectrum (CI, NH_3, positive ion), 302 (M + NH_4^+ – PTADH$_2$), 284 (base M + H^+ – PTADH$_2$), (NH_3, negative ion) 460 (M^-), 283 (M – H^+ – PTADH). This diadduct was further characterized as its diacetamide (Ac_2O, CH_2Cl_2; preparative TLC purification with 1:2 hexanes–EtOAc elution, colorless oil): ^{1}H NMR ($CDCl_3$) δ 2.10 (m, 2 H, $COCH_2CH_2$), 2.3–2.7 (m, 4 H), 2.60 (s, 6 H, $NCOCH_3$), 4.93 (br s, 2 H, CH_2N), 7.5 (br s, 10 H, Ar H); IR ($CHCl_3$) 3040, 2950, 1800, 1740, 1680, 1630, 1600, 1500, 1410, 1370, 1240, 1010 cm^{-1}; mass spectrum (CI, NH_3, positive ion), 562 (M + NH_4^+), 545 (M + H^+), (NH_3, negative ion) 501 (M + NH_2^- – CH_3CONH_2), 459 (M + NH_2^- + NH_3 – 2 CH_3CONH_2), 283 (M + NH_2^- – CH_3CONH_2 – PTADH). Anal. Calcd for $C_{27}H_{25}O_7N_6$ (M + H^+, no molecular ion detectable under 20 eV EI conditions): *m/e* 545.1784. Found: *m/e* 545.1782. Calcd for $C_{25}H_{22}O_6N_6$ (M – CH_2CO): *m/e* 502.1600. Found: *m/e* 502.1584.

1-(1-Acetyl-2-methyl-1-propenyl)-4-phenyl-1,2,4-triazolidine-3,5-dione (3c). Adduct **2c** (0.213 g) and silica gel (2 g) were refluxed in benzene for 2 h. Filtration and solvent removal provided a quantitative recovery of **3c**. Recrystallization from acetone–hexanes (5×) gave an analytical sample: mp 208–210.5 °C; ^{1}H NMR ($CDCl_3$) δ 2.01, 2.21, and 2.23 (3 s, 3 H, CH_3), 7.45 (br s, 5 H, Ar H); IR (KBr) 3060, 2920, 2850, 1770, 1695, 1640, 1595, 1495, 1450, 1410, 1320, 1210, 1145, 800, 770, 725, 695, 690, 640 cm^{-1}; mass spectrum (EI), *m/e* (relative intensity) 273 (20), 230 (15), 187 (17), 68 (90), 43 (100). Anal. Calcd for $C_{14}H_{15}N_3O_3$: C, 61.53; H, 5.53; N, 15.38. Found: C, 61.63; H, 5.49; N, 15.19.

2-Acetyl-1-[1-(1-cyclopentenyl)-2-oxocyclopentyl]-4-phenyl-1,2,4-triazolidine-3,5-dione (3h) and 2-Acetyl-1-[1-(5-oxo-1-cyclopentenyl)cyclopentyl]-4-phenyl-1,2,4-triazolidine-3,5-dione (3h'). A crude solution of **2h** and **2h'** (542 mg) in methylene chloride (4 mL) was treated with acetic anhydride (720 μL) and pyridine (700 μL) at room temperature. Dilution with CH_2Cl_2, washing with 10% HCl (2×) and brine (1×), drying ($MgSO_4$), and concentration afforded crude **3h** and **3h'** which were purified on silica gel (1:1 hexanes–EtOAc elution) to give the less polar **3h'** (259 mg, 0.706 mmol, 43%) and **3h** (304 mg, 0.828 mmol, 50%) as slightly yellow crystals. Recrystallization of **3h'** from benzene/hexanes and of **3h** from hexanes/EtOAc gave analytical samples. **3h'**: mp 132–134 °C; ^{1}H NMR ($CDCl_3$) δ 1.5–2.7 (m, 12 H), 2.57 (s, 3 H, $COCH_3$), 7.4 (br s, 5 H, Ar H), 7.51 (t, J = 3 Hz, 1 H, C=CH); IR ($CDCl_3$) 2970, 2900, 1735, 1705, 1600, 1410, 1220 cm^{-1}; mass spectrum (CI, NH_3, positive ion), 385 (M + NH_4^+), 368 (M + H^+). Anal. Calcd for $C_{20}H_{21}N_3O_4$: C, 65.38; H, 5.76; N, 11.44. Found: C, 65.32; H, 5.88; N, 11.40. **3h**: mp 121–123 °C; ^{1}H NMR ($CDCl_3$) δ 1.6–2.9 (m, 12 H), 2.53 (s, 3 H, $COCH_3$), 5.96 (br s, 1 H, C=CH), 7.42 (s, 5 H, Ar H); IR ($CDCl_3$) 2950, 1765, 1730, 1715, 1620, 1595, 1500, 1410, 1240 cm^{-1}; mass spectrum (CI, NH_3, positive ion), 385 (M + NH_4^+), 368 (M + H^+). Anal. Found: C, 65.61; H, 5.81; N, 11.40.

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Registry No. **1a**, 74542-27-1; **1b**, 625-33-2; **1c**, 141-79-7; **1d**, 80-62-6; **1e**, 932-66-1; (*Z*)-**1f**, 7417-54-1; (*E*)-**1f**, 7417-55-2; (*Z*)-**1g**, 43142-59-2; (*E*)-**1g**, 43142-58-1; **1h**, 825-25-2; **1i**, 89-82-7; **1j**, 74542-28-2; **1k**, 74542-29-3; **1l**, 1121-18-2; **2a** (isomer 1), 74542-30-6; **2a** (isomer 2), 74561-77-6; **2b**, 74542-31-7; **2c**, 62407-64-1; **2d**, 74542-32-8; **2e**, 74542-33-9; **2f**, 74542-34-0; **2g**, 74542-35-1; **2h**, 74542-36-2; **2h'**, 74542-37-3; **2i** (epimer 1), 62407-65-2; **2i** (epimer 2), 62446-39-3; **2j**, 74542-38-4; (*Z*)-**2k**, 74552-05-9; (*E*)-**2k**, 74542-39-5; **2l**, 74552-06-0; **3c**, 74552-07-1; **3h**, 74552-08-2; **3h'**, 74542-40-8; **4d**, 74542-41-9; **4e**, 74542-42-0; 1-(trimethylsiloxy)cyclohexene, 6651-36-1; 1,1,1-trifluoroacetone, 421-50-1; (*R,R*)-2-(1-hydroxy-1-methyl-2,2,2-trifluoroethyl)cyclohexanone, 74542-43-1; (*R,S*)-2-(1-hydroxy-1-methyl-2,2,2-trifluoroethyl)cyclohexanone, 74542-44-2; PTAD, 4233-33-4.

Configurations and Chemistry of the Perfluorotricyclo[4.2.0.0^{2,5}]octa-3,7-dienes

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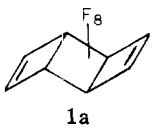
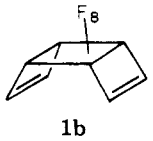
Irradiation at 2537 Å of perfluorocyclooctatetraene yielded *anti*- and *syn*-perfluorotricyclo[4.2.0.0^{2,5}]octa-3,7-dienes **1a** and **1b**, respectively, which reverted quantitatively to the tetraene at 150 °C. Bromine addition occurred exclusively in the exo, suprafacial fashion with both dienes, but only the anti isomer added 2 mol of bromine. The latter fact, together with analysis of the ^{19}F NMR spectra of the bromine adducts, constitutes convincing evidence for the configurational assignments for **1a** and **1b**. Perfluorobenzene underwent [2 + 2] photocycloaddition with chlorotrifluoroethylene, and the bicyclic adducts suffered photochemical electrocyclization to a stereoisomeric mixture of 7-chlorotricyclo[4.2.0.0^{2,5}]oct-3-enes. Analysis of the ^{19}F NMR spectra of the major isomers permitted their assignment as exo,anti and endo,anti. Reduction of the former gave **1a**, thus confirming the diene's configuration. An explanation based on "second-order" orbital symmetry effects is suggested for the syn/anti stereoselectivity found in the thermal and photochemical electrocyclic processes described above.

Irradiation of perfluorocyclooctatetraene[1,2] in the vapor phase at 2537 Å in an atmosphere of nitrogen yields a 20:1 mixture of the stereoisomeric title compounds.[3] They are volatile crystalline solids melting at 40–41.5[5] and 51–53 °C, respectively, which revert cleanly to their progenitor when heated at 150 °C.[6] Assignment of configuration to this pair of dienes is required for understanding the photochemistry of perfluorobenzene as well as perfluorocyclooctatetraene, as will become apparent. The chemistry of the dienes and analysis of the ^{19}F NMR spectra of various derivatives have revealed clearly which is anti (**1a**) and which syn (**1b**). These matters form the substance of the present report.



1a

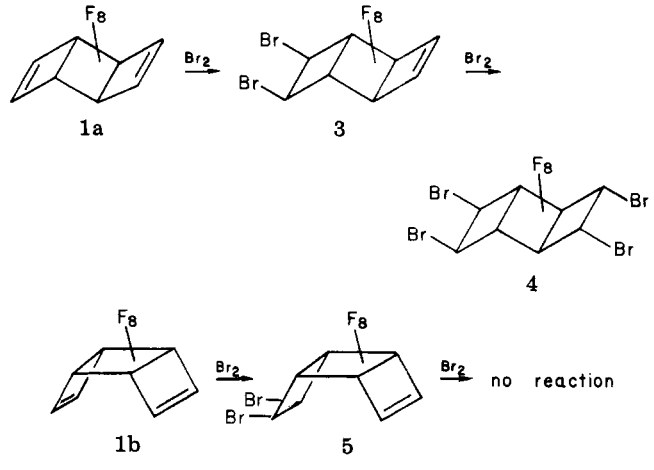


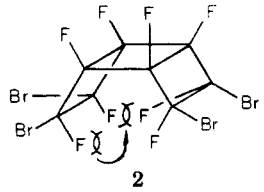
1b

Results and Discussion

Bromine Adducts. Each diene reacts smoothly with bromine in carbon tetrachloride at room temperature to give a single dibromide. The higher melting diene reacts about 3 times as fast as the lower, but the reaction ceases abruptly after consumption of 1 mol of bromine. In contrast, the dibromide formed from the 41 °C isomer adds a second mole easily enough that tetrabromide accompanies the dibromide before the starting diene is fully consumed, even when the reaction is carried out at −20 °C. These facts are easily understood if, and only if, *the low-melting isomer has the anti and the high-melting diene the syn configuration.* Models confirm that the double bond of a dibromide derived from **1a** can be comparably reactive to those of **1a** itself but that the double bond of a dibromide formed from **1b** should powerfully resist further addition. Even the least strained tetrabromide **2**

Scheme I





2

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(2) D. M. Lemal, J. M. Buzby, A. C. Barefoot, III, M. W. Grayston, and E. D. Laganis, *J. Org. Chem.*, **45**, 3118 (1980).

(3) Formation of tricyclo[4.2.0.0^{2,5}]octa-3,7-dienes by ultraviolet irradiation of a cyclooctatetraene is highly unusual, but it finds a precedent in the behavior of perfluorooctamethylcyclooctatetraene.[4]

(4) L. F. Pelosi and W. T. Miller, Jr., *J. Am. Chem. Soc.*, **98**, 4311 (1976).

(5) The lower melting isomer has been reported as the product of vapor-phase photolysis of tetrafluorocyclobutene-3,4-dicarboxylic anhydride in an atmosphere of nitrogen.[1] Contrary to the original interpretation, it is now clear that most, if not all, of the tricyclooctadiene is formed in this experiment by photocyclization of perfluorocyclooctatetraene (which is dramatically accelerated by an inert gas).

(6) This behavior parallels that of their hydrocarbon counterparts. (a) M. Avram, I. G. Dinulescu, E. Marica, G. Mateescu, E. Sliam, and C. D. Nenitzescu, *Chem. Ber.*, **97**, 382 (1964). (b) H. M. Frey, H.-D. Martin, and H. Hekman, *J. Chem. Soc., Chem. Commun.*, 204 (1975).

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