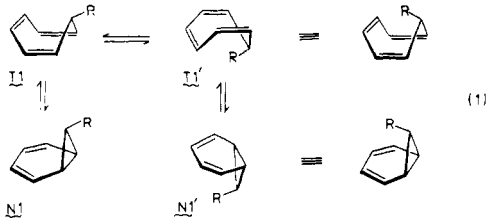
Reaction of 7-Substituted Cycloheptatrienes with Singlet Oxygen and 4-Phenyl-1,2,4-triazoline-3,5-dione[1]

Waldemar Adam,*[2] Metin Balci, and Barbara Pietrzak

Contribution from the Department of Chemistry, University of Puerto Rico, Río Piedras, Puerto Rico 00931. *Received March 20, 1979*

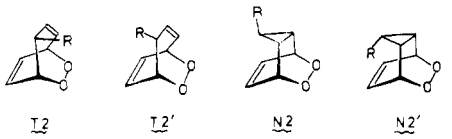
Abstract: A series of 7-substituted cycloheptatrienes **1**, including the CN, CO_2CH_3, CHO, OCH_3, and C_6H_5 groups, has been submitted to photosensitized singlet oxygenation and reaction with 4-phenyl-1,2,4-triazoline-3,5-dione. The yields of the norcaradiene-type and tropilidene-type adducts **2** ($^1O_2$) and **3** (PTAD) were determined to probe the effect of the π-acceptor and π-donor properties of these substituents on the cycloheptatriene valence tautomerization equilibrium. From the yields of exo and endo products, the steric effect of the 7-substituent on the ring inversion equilibrium was examined. The novel endoperoxides **2** of the 7-substituted cycloheptatrienes were characterized by diimide reduction to their saturated cyclic peroxides **4**, thermal isomerization to their bisepoxides **5**, and deoxygenation with triphenylphosphine to their epoxy olefins **6**.

Cycloheptatriene **1** can be a complex dienic substrate in view of its unique property to ring-invert and cyclotautomerize.[3] These processes are illustrated in eq 1 for 7-substituted



(1)

cycloheptatrienes, where R designates substituents at the C-7 position, and **T** and **N** the tropilidene and norcaradiene valence isomer structures. The activation energy for the ring inversion process is ca. 9–19 kcal/mol[4] and for the cyclotautomerization ca. 10 kcal/mol.[5] Therefore, theoretically the four (2 + 4)-cycloadducts **T2, T2', N2,** and **N2'** are possible, using singlet oxygen as the dienophile for illustration.[6] The actual product composition should depend on the size of the 7 substituents and its electronic nature (eq 1). For example, large R groups should favor the exo isomers **T2** and **N2**,[7] while electron-withdrawing



(by resonance) R groups should favor the norcaradiene isomer.[8]

Recently[9] we observed that 7-cyanocycloheptatriene **1a** reacted with singlet oxygen to afford a 1.2:1 mixture of the norcaradiene-derived (2 + 4)-adducts **N2a** and **N2a'**, respectively, where R = CN. Similarly, the very dienophilic 4-phenyl-1,2,4-triazoline-3,5-dione (PTAD) led to a 1.5:1 mixture of the (2 + 4)-cycloadducts **N3a** and **N3a'**, respectively. Careful ^1H NMR analysis of the product mixtures did not reveal even traces of the corresponding tropilidene (2 + 4)-cycloadducts. Clearly, our cycloaddition results with $^1O_2$ and with PTAD imply that ring inversion and cyclotautomerization (eq 1) are taking place concurrently. Although in this complex equilibrium the tropilidene isomers predominate, the norcaradiene isomers must exhibit a much greater dienic reactivity. Otherwise, small quantities of tropilidene-type (2 + 4)-adducts should have been detected at least with the very reactive PTAD.

In view of these interesting results with the 7-cyanocycloheptatriene system, we decided to investigate the dienic reactivity of other 7-substituted cycloheptatrienes, including R = CO_2CH_3 (**1b**), R = CHO (**1c**), R = OCH_3 (**1d**), and R = Ph (**1e**), toward singlet oxygen and PTAD. Herein we describe the full details of our study.

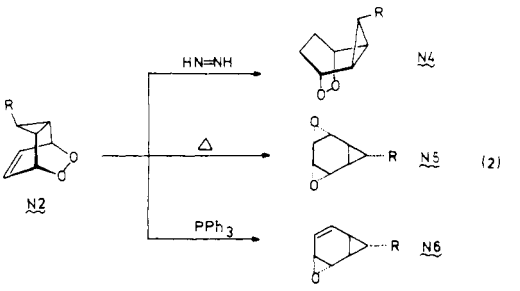
Results and Discussion

1. Synthesis of 7-Substituted Cycloheptatriene 1. Tropilium bromide was the starting material for the preparation of the 7-substituted 1,3,5-cycloheptatrienes **1** except the carboxaldehyde derivative **1c.** The tropilium bromide was prepared according to Doering and Knox,[10] but higher yields and purer product could be obtained by effecting the dehydrobromination at 100 °C at 10 mmHg for 2 h instead of the previously prescribed 60–65 °C at 15–20 mmHg for 72 h. Thus, treatment of tropilium bromide with potassium cyanide[10] gave **1a** and with sodium methoxide[11] **1d** was obtained. Methanolysis of **1a** afforded **1b.**[12] For the preparation of **1e,** instead of tropilium bromide, it was advantageous to treat the methoxy derivative **1d** with phenylmagnesium bromide.[13] The 1,3,5-cycloheptatriene-7-carboxaldehyde (**1c**) was prepared via bis(chlorodicarbonylrhodium) complex catalyzed isomerization of cyclooctatetraene epoxide.[14]

2. Singlet Oxygenation Adducts 2. Like the 7-cyano derivative **1a,** the other 7-substituted cycloheptatrienes also reacted smoothly with singlet oxygen to afford the corresponding endoperoxides **2.** The results are summarized in Table I. These relatively stable endoperoxides could be rigorously purified by silica gel column chromatography and/or recrystallization. All new substances gave satisfactory elemental analyses. The ^1H NMR and IR spectral data (Table I) support the proposed structures.

Extensive ^1H NMR decoupling experiments were necessary to confirm the structure assignments of the (2 + 4)-cycloadducts **T2d** (R = OCH_3) and **T2e** (R = C_6H_5). The coupling constants are also listed in Table I.

As additional structural proof we relied on chemical transformations, including (a) diimide reduction, (b) thermal isomerization, and (c) triphenylphosphine deoxygenation, as illustrated for the norcaradiene endoperoxides **N2** (eq 2).

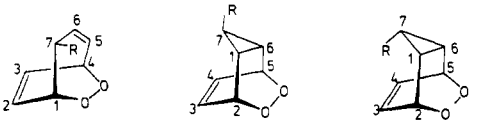


(2)

The results of the diimide reduction, carried out as described by us previously,[15] are given in Table II. The aldehyde deriv-

0002-7863/79/1501-6285$01.00/0

Table I. Yields, Physical Constants, and Spectral Data of Endoperoxides **2**



T2 N2 N2

endoperoxide	R	yield, %	physical constants mp, °C bp, °C/mm n_D^{25}	^{1}H NMR type	no. of protons	δ, ppm	multiplicity[a]	J, Hz	IR, cm^{-1} ν_{C-H}	ν_R
N2a	CN	42	107–108[b] (CH_2Cl_2/ CCl_4)	H_7[c]	1	0.98	t	3.28	3030 m[d]	2240 w
				$H_{1,6}$	2	2.22	m		2980 w	
				$H_{2,5}$	2	4.70–5.10	m		2917 w	
				$H_{3,4}$	2	6.10[e]	t′			
N2a′	CN	33	194–195[b] (MeOH)	H_7[c]	1	1.45	t	7.90	3030 m[f]	2230 w
				$H_{1,6}$	2	2.00–2.30	m			
				$H_{2,5}$	2	4.80–5.20	m			
				$H_{3,4}$	2	6.20–6.50[e]	t′			
N2b	CO_2Me	84	93–95[g] (MeOH)	H_7[c]	1	1.14–1.30	t	3.20	3050 m[h]	1730 s
				$H_{1,6}$	2	2.04–2.30	m		3020 m	
				OMe	3	3.53	s		2963 m	
				$H_{2,5}$	2	4.66–5.00	m			
				$H_{3,4}$	2	5.98–6.26	m			
N2c	CHO	58	95–96[b] (CH_2Cl_2/ C_5H_{12})	H_7[c]	1	1.35–1.60	m		3070[d]	1715 s
				$H_{1,6}$	2	2.10–2.40	m		2980 m	
				$H_{2,5}$	2	4.70–5.00	m		2950 m	
				$H_{3,4}$	2	6.10	t′		2900 w	
				CHO	1	8.93	d	4.12	2840 m	
T2d	OMe	67	1.5155[b,i]	OMe[j]	3	3.26	s	$J_{1,6}$ 1.6	3075 w[j]	1095 s
				H_7	1	3.85	m	$J_{2,3}$ 8.6	3050 w	
				H_4	1	4.40	brt	$J_{3,4}$ 5.6	2995 w	
				H_1	1	4.80	brt	$J_{4,5}$ 5.9	2940 m	
				H_6	1	5.35–5.70	m	$J_{5,6}$ 10.2	2860 w	
				$H_{5,2}$	2	5.80–6.20	m	$J_{6,7}$ 2.4	2833 m	
				H_3	1	6.35–6.70	brdd			
T2e	Ph	3	113–114 (Et_2O/ C_5H_{12})	H_7[c]	1	4.05	m	$J_{1,2}$ 5.9	3070 w[h]	1600 m
				$H_{1,4}$	2	4.40–4.90	m	$J_{3,4}$ 7.0	3043 w	
				$H_{2,6}$	2	5.30–5.90	m	$J_{4,5}$ 6.83	2970 w	
				H_5	1	5.90–6.30	ddd	$J_{5,6}$ 10.16	2935 m	
				H_3	1	6.35–6.75	dd			
				Ph	5	6.80–7.20	m			
N2e	Ph	61	94–96[b] (Et_2O/ C_5H_{12})	H_7[j]	1	1.26–1.50	t	3.16	3090 w[j]	1605 m
				$H_{1,6}$	2	1.56–2.00	m		3070 m	
				$H_{2,5}$	2	4.40–4.80	m		3040 m	
				$H_{3,4}$	2	5.83–6.23	t′		2960 m	
				Ph	5	6.48–7.10	m			

[a] Primed notation denotes second-order splitting. [b] Elemental analysis was within acceptable limits of 0.3% for C and 0.2% for H. [c] Recorded in $CDCl_3$. [d] KBr pellet. [e] AA′ part of AA′XX′ system. [f] Nujol mull. [g] Ritter, A.; Bayer, P.; Leitich, J.; Schomburg, G. *Justus Liebigs Ann. Chem.* **1974,** 835; mp 95 °C (MeOH). [h] Recorded in $CHCl_3$. [i] Purified by silica gel chromatography, eluting with 1:1 CH_2Cl_2/C_5H_{12}. [j] Recorded in CCl_4.

ative **N2c** led to an intractable material. All saturated peroxides **T4** and **N4** are new compounds and exhibited satisfactory elemental analyses. The ^{1}H NMR and IR data clearly establish the proposed structures. As can be expected, the saturated bicyclic peroxides **4** are thermally considerably more stable than the unsaturated endoperoxides **2**.

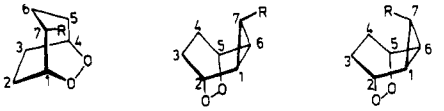
On heating the norcaradiene-derived endoperoxides **N2,** the corresponding bisepoxides **N5** were obtained in high yield (Table III). Again, all new bisepoxides **N5** gave satisfactory elemental analysis. The ^{1}H NMR and IR data corroborate the proposed structures.

The triphenylphosphine deoxygenations are summarized in Table IV. The resulting monoepoxy olefins **N6** have been fully characterized on the basis of correct elemental analysis and spectral data.

3. 4-Phenyl-1,2,4-triazoline-3,5-dione Adducts 3. The 7-substituted cycloheptatrienes **1** gave exclusively the norcaradiene-type (2 + 4)-cycloadducts with PTAD (Table V). In fact, only the cyano derivative **1a** gave a mixture of *exo*-**N3a** and *endo*-**N3a′** products; the others only afforded the corresponding exo isomers. All PTAD cycloadducts gave satisfactory elemental analysis and the spectral data confirm the proposed norcaradiene adducts.

4. ^{1}H NMR Spectra. The NMR spectra were quite complex for most of the compounds described in this study so that extensive decoupling experiments had to be performed to unravel

Table II. Yields, Physical Constants, and Spectral Data of Cyclic Peroxides **4**



T4 N4 N4'

	R	yield, %	physical constants mp, °C bp, °C/mm n_D^{25}	^{1}H NMR type	no. of protons	δ, ppm	multiplicity	IR, cm^{-1} ν_{C-H}	ν_R
N4a	CN	59	152–154 dec (CH_2Cl_2/C_5H_{12})[a]	$H_{1,6,7}$[b]	3	1.20–1.80	m	2980 m[c]	2250 m
				$H_{3,4}$	4	1.80–2.50	m	2960 s	
				$H_{2,5}$	2	4.20–4.50	m		
N4a'	CN	87	140 dec (CH_2Cl_2/C_5H_{12})[a]	$H_{1,3,4,6,7}$[b]	7	1.55–2.40	m	2960 s[c]	2245 m
				$H_{2,5}$	2	4.30–4.60	m		
N4b	CO_2Me	88	160.5–162.5[a] (CH_2Cl_2/C_5H_{12})	H_3[b]	4	1.20–2.30	m	2970 m[d]	1735 s
				H_7	1	1.70	t		
				$H_{1,6}$	2	2.10–2.35	m		
				Me	3	3.58	s		
				$H_{2,5}$	2	4.20–4.50	m		
T4d	OMe	71	63–64/0.3 n_D^{20} 1.4820	$H_{2,3,5,6}$[e]	8	1.22–2.26	m	2943 s[e]	1097 s
				H_7	1	3.00–3.55	m	2880 m	
				OMe	3	3.15	s	2830 m	
				$H_{1,4}$	2	3.73–4.36	m		
T4e	Ph	68	n_D^{20} 1.5601 83/0.30	$H_{2,3,5,6}$[e]	8	1.50–2.35	m	3100 w[e]	1610 w
				H_7	1	3.00–3.50	m	3080 w	
				$H_{1,4}$	2	3.90–4.45	m	3045 m	
				Ph	5	6.92	s	2950 m	
								2940 m	
								2850 w	
N4e	Ph	92	112–113[a] (CH_2Cl_2/C_5H_{12})	$H_{1,3,4,6,7}$[e]	7	1.15–2.25	m	3095 w[e]	1605 m
				$H_{2,5}$	2	4.15	brs	3070 w	
				Ph	5	6.60–7.10	m	3040 m	
								2953 m	
								2910 w	
								2880 w	

[a] Elemental analysis was within acceptable limits of 0.3% for C and 0.2% for H. [b] Recorded in $CDCl_3$. [c] Recorded in $CHCl_3$ and as KBr pellet. [d] Recorded in $CHCl_3$. [e] Recorded in CCl_4.

the structural details. However, this also offered a powerful tool in the structure elucidation of the reported compounds, e.g., the tropilidene endoperoxides **T2** (cf. Table I).

The norcaradiene endoperoxides **N2** exhibited spectra consistent with an AA'MM'XX'Z system (cf. Table I). The AA' part of the double bond protons ($H_{3,4}$) shows up as a quasitriplet. Furthermore, irradiation of the cyclopropane protons ($H_{1,6}$) collapses the multiplet of the bridgehead protons ($H_{2,5}$) into the expected quasitriplet for the MM' part of the AA'MM' system. The line broadening in the MM' part indicates a small coupling with the H_7 proton.

The norcaradiene-type (2 + 4)-adduct with PTAD, i.e., **N3**, shows ^{1}H NMR spectra similar to the norcaradiene endoperoxides **N2**. The smaller coupling constants $J_{1,7} = J_{6,7} = 1.4$ Hz for the methoxy derivative **N3d** are due to the oxygen atom of the methoxy substituent.[16]

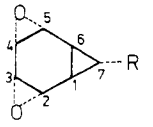
For the bisepoxides **N5** the NMR spectra are greatly simplified because the signals of the four epoxy protons all collapse into a singlet, leaving just the AB_2 system of the cyclopropane protons. The actual appearance of the spectrum depends on the chemical shift differences of the A and B protons.

Again, as expected, the epoxy olefins **N6** give rise to rather complex spectra, but double resonance was invaluable in assigning the structures. Thus, decoupling experiments permitted assignment of the high field δ 2.6–2.9 ppm resonance (cf. Table V) to the epoxide H_3 proton. By detailed analysis of the low field δ = 3.4–3.6 ppm doublet of doublets of the epoxide H_2 proton, the small $J_{1,2} = 1.74$ Hz coupling constant value could be extracted. The coupling constants[17] and Dreiding models confirm that the epoxide rings are anti to the cyclopropane ring, causing an essentially planar cyclohexane conformation.

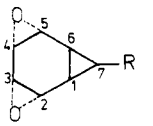
5. Mechanistic Implications. Our product composition data for the singlet oxygenation (Table I) of the 7-substituted cycloheptatrienes reveal qualitatively that the norcaradiene-derived (2 + 4)-adduct **N2** increases at the expense of the tropilidene-derived (2 + 4)-adduct **T2** in the order CHO ~ CO_2Me ~ CN > Ph > H > MeO, being exclusively **T2** for MeO and exclusively **N2** for CN, CO_2Me, and CHO. For H mainly **T2**[18] and for Ph mainly **N2** are formed. On the other hand, with PTAD (Table V) only the norcaradiene (2 + 4)-adduct **3** is produced for all substituents. This interesting substituent effect for $^1O_2$, but the lack of it for PTAD, demand rationalization.

A theoretical analysis[8] of substituents at the 7 position of cycloheptatriene on the dynamic tropilidene–norcaradiene equilibrium suggested that π-electron acceptors, e.g., CN, CO_2Me, and CHO, should stabilize the cyclopropane ring and

Table III. Yields, Physical Constants, and Spectral Data of Bisepoxides **5**



5



5

	R	yield, %	physical constants mp, °C bp, °C/mm n_D^{25}	^{1}H NMR ($CDCl_3$) type	no. of protons	δ, ppm	multiplicity	J, Hz	IR ($CHCl_3$), cm^{-1} ν_{C-H}	ν_R
5a	CN	100	159–160[a,b] (CH_2Cl_2/ C_5H_{12})	H_7	1	1.45	t	4.6	2990 w[c]	2245 m
				$H_{1,6}$	2	2.08	d	4.6	2960 w	
				$H_{2,3,4,5}$	4	3.20	s			
5a′	CN	100	199–200 (CH_2Cl_2/ C_5H_{12})	$H_{1,6,7}$	3	1.88	s		2980 w[c]	2245 m
				$H_{2,3,4,5}$	4	3.20–3.50	m		2900 w	
5b	CO_2Me	100	114–115[a,d] (C_6H_6/ C_6H_{12})	H_7	1	1.70	t	4.5	3003 m	1727 s
				$H_{1,6}$	2	2.01	d	4.5	2955 m	
				$H_{2,3,4,5}$	4	3.15	s			
				Me	3	3.58	s			
5c	CHO	100	145–148[a] (CH_2Cl_2/ Et_2O)	$H_{1,6,7}$	3	1.80–2.30	m		2840	1700 s
				$H_{2,3,4,5}$	4	3.15	s		2730	
				Me	1	8.95	d	~4		
5e	Ph	100	149–150[a] (C_6H_6/ C_6H_{12})	$H_{1,6,7}$	3	1.70–2.12	m		3090 w	1615 m
				$H_{2,3,4,5}$	4	3.21	s		3080 m	
				Ph	5	6.65–7.30	m		3040 m	
									3020 s	
									2975 w	

[a] Elemental analysis was within acceptable limits of 0.3% for C and 0.2% for H. [b] Kabuto, C.; Yagihara, M.; Asao, T.; Kitahara, Y. *Angew. Chem.* **1973,** *85,* 860; mp 104–105 °C. [c] Also recorded as KBr pellet. [d] Ritter, A.; Bayer, P.; Leitich, J.; Schomburg, G. *Justus Liebigs Ann. Chem.* **1974,** 835; mp 117 °C (C_6H_{12}).

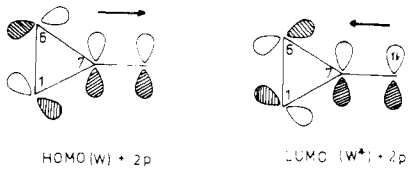
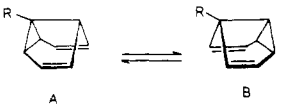


Figure 1.

thus shift the equilibrium toward the norcaradiene tautomer **N1,** while π-electron donors, e.g., MeO, should destabilize the cyclopropane ring and thus shift the equilibrium toward the tropilidene tautomer **T1.** This effect of the 7 substituent is exercised through interaction of the π orbitals of the substituent with the Walsh orbitals of the cyclopropane moiety (Figure 1). Thus, an empty 2p orbital (taken as model for the acceptor) on the substituent R at C-7 of cycloheptatriene interacts via electron acceptance with the HOMO Walsh orbital (W) of the cyclopropane ring leading to diminished antibonding between carbons C-1 and C-6. Consequently, this stabilizing interaction of the CN, CO_2Me, and CHO substituents benefits the norcaradiene structure. In fact, for the semibullvalene valence tautomerization shown in eq 3, ex-



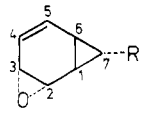
(3)

tended Hückel theory calculations predicted[19] that the stabilization energies (ΔE) should be 0.37, 0.40, and 0.43 eV respectively for CN, CO_2H, and CHO in favor of isomer A. On the other hand, an occupied 2p orbital (taken as model for the π donor) on the substituent R interacts via electron donation with the LUMO Walsh orbital (W*) of the cyclopropane ring leading to increased antibonding between C-1 and C-6. Consequently, such destabilizing interaction of the MeO substituent benefits the tropilidene structure.

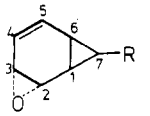
Fortunately, experimental data are available, corroborating this theoretical conclusion. For example, while for the unsubstituted cycloheptatriene no norcaradiene valence tautomer could be detected by variable-temperature ^{1}H NMR even down to −150 °C,[20] for the 7-carboxylic acid derivative ca. 3% norcaradiene isomer could be observed[21] under these conditions. More dramatic, with two π-acceptor substituents, e.g., CN, at the 7 position, the norcaradiene tautomer is the more stable form by ca. 6 kcal,[22] which should be contrasted with the unsubstituted cycloheptatriene where the tropilidene tautomer is the more stable form by ca. 11 kcal.[23] Consequently, the *gem*-cyano substituents cause a stabilization of the norcaradiene tautomer of ca. 17 kcal/mol or 0.74 eV, which corresponds approximately to 0.37 eV per CN substituent. The agreement between theory[19] and experiment[21] is remarkable.

In the semibullvalene valence tautomerization, extensively investigated by Paquette and co-workers,[24] the experimental observations as well substantiate the theoretical conclusions.[19] Thus, on cyano substitution the valence isomer A prevails in the valence tautomeric equilibrium of eq 3. Furthermore, very recently Tufariello and colleagues[25] have shown that, in the thermal stereomutation of 5-substituted bicyclo[2.1.0]pentanes, the activation energy is substantially lower (10–12 kcal/mol) for π donors (OR) compared with π acceptors (CN). Again this has been rationalized in terms of weakening the transannular bond due to π donation by OR and strengthening it due to π acceptance by CN.

Table IV. Yields, Physical Constants, and Spectral Data of Epoxy Olefins **6**



6



6'

	R	yield, %	physical constants mp, °C bp °C/mm n_D^{25}	^{1}H NMR ($CDCl_3$) type	no. of protons	δ, ppm	multiplicity	J, Hz	IR ($CHCl_3$), cm^{-1} ν_{C-H}	ν_R
6a	CN	100	n_D^{25} 1.5045[a]	H_7	1	1.45-1.60	t	$J_{1,2}$ 1.76	3020 w	2220 m
				H_6	1	1.65-2.00	dd	$J_{1,6}$ 6.66	2940 w	
				H_1	1	2.15-2.45	ddd	$J_{2,3}$ 3.99		
				H_3	1	2.70-2.90	m	$J_{3,4}$ 3.99		
				H_2	1	3.40-3.60	dd	$J_{3,5}$ 1.49		
				$H_{4,5}$	2	5.40-6.00	m	$J_{4,5}$ 9.33		
								$J_{5,6}$ 3.49		
								$J_{6,7}$ $J_{1,7}$ } 4.33		
6a'	CN	85	98[a] (CH_2Cl_2/C_5H_{12})	$H_{1,6,7}$	3	1.60-2.40	m		3050 w[b]	2245 m
				H_3	1	2.85-3.10	m		2980 w	
				H_2	1	3.45-3.65	dd			
				$H_{4,5}$	2	5.75-5.90	m			
6b	CO_2Me	96	109/1.0-1.2 51-52[a] (subl 65 °C at 0.35 mm)	$H_{6,7}$	2	1.50-1.90	m	$J_{1,2}$ 1.73	3050 m	1725 s
				H_1	1	2.10-2.40	m	$J_{2,3}$ 4.05	3020 m	
				H_3	1	2.60-2.80	m	$J_{3,4}$ 3.5	2970 m	
				H_2	1	3.40	dd	$J_{3,5}$ 1.33		
				Me	3	3.50	s	$J_{4,5}$ 9.5		
				$H_{4,5}$	2	5.30-6.00	m	$J_{5,6}$ 3.42		
6e	Ph	98	123/0.85 46.5-48.5 (subl 65-70 °C at 0.3 mm)	H_6	1	1.30-1.70	m	$J_{2,3}$ 3.99	3040 m	1610 m
				$H_{1,7}$	2	1.90-2.30	br d	$J_{3,4}$ 3.34	3025 m	
				H_3	1	2.85	m	$J_{3,5}$ 1.50	2990 w	
				H_2	1	3.60	m	$J_{4,5}$ 8.70		
				$H_{4,5}$	2	5.25-6.30	m	$J_{5,6}$ 4.06		
				Ph	5	6.70-7.10	m			

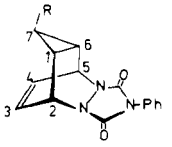
[a] Elemental analysis was within acceptable limits of 0.3% for C and 0.2% for H. [b] Also recorded as KBr pellet.

Let us now apply these interesting theoretical[8,19] and experimental[20-25] findings on the dynamic equilibrium of the norcaradiene-tropilidene valence tautomerization to our singlet oxygen results. The fact that the π-donating MeO substituent leads only to the tropilidene (2 + 4)-adduct **T2** and the π-accepting CN, CO_2Me, and CHO substituents afford only the norcaradiene (2 + 4)-adduct **N2,** while for Ph both the **T2** and **N2** adducts were formed with **N2** predominating and for the unsubstituted cycloheptatriene also both the **T2** and **N2** adducts are produced but now **T2** is predominating, established that the dienophilic singlet oxygen is sensing the substituent effect on the tropilidene-norcaradiene valence tautomerization. Clearly, singlet oxygen intervenes in the **T1** ⇌ **N1** dynamic equilibrium (eq 1). This is not surprising since a recent kinetic study confirms[26] that the dienophilic reactivity of singlet oxygen toward (2 + 4)-cycloaddition is enormous, i.e., $\Delta H^{\ddagger} \sim 0$, $\Delta S^{\ddagger} \sim -20$ to -25 eu, and $\Delta G^{\ddagger}_{300K} \sim 6$-8 kcal/mol. In fact, the activation free energy is entirely entropy controlled and essentially diffusion controlled from the point of view of the activation enthalpy. Thus, the MeO π donor displaces the **T1** ⇌ **N1** dynamic equilibrium to the side of the tropilidene valence isomer **T1** and the activation barrier for cycloaddition of $^1O_2$ with **T1** must be significantly lower than the activation barrier for its valence isomerization to the norcaradiene tautomer **N1.** Consequently, the **T1** ⇌ **N1** dynamic equilibrium is syphoned off through **T1** in the case of MeO and only the **T2** (2 + 4)-adduct results.

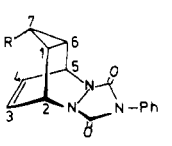
On the other hand, in the case of the CN π acceptor, for example, the **T1** ⇌ **N1** dynamic equilibrium is still on the side of the tropilidene valence isomer **T1** (no norcaradiene valence isomer **N1** could be detected[21] even at −150 °C). However, the activation barrier for the cycloaddition of **T1** with $^1O_2$ to give the **T2** adduct for CN must be significantly higher than the activation barrier for the **T1** ⇌ **N1** valence isomerization, which in turn must be higher than the activation barrier for the cycloaddition of **N1** with $^1O_2$ to give the **N2** adduct. This is not surprising since the planar diene moiety in norcaradiene should be considerably more reactive toward dienophiles than the twisted diene moiety in tropilidene. In other words, in the case of CN, CO_2Me, and CHO the valence isomerization is faster than the reaction of **T1** with $^1O_2$, but reaction of **N1** with $^1O_2$ is still faster than the valence isomerization. Consequently, the **T1** ⇌ **N1** dynamic equilibrium is syphoned off through **N1** for these π acceptors and only the **N2** (2 + 4)-adduct is observed.

For the Ph substituted and the unsubstituted cycloheptatriene, a balance is struck between these two trends since both the **T2** and **N2** (2 + 4)-adducts are formed. In the case of phenyl, the activation barrier for the **T1** ⇌ **N1** dynamic equilibrium must be comparable to that of the cycloaddition reaction **N1** + $^1O_2$ → **N2,** but both greater than that of the cycloaddition reaction **T1** + $^1O_2$ → **T2.** Consequently, more **N2** than **T2** adduct is formed. The π-donating and π-accepting ability of phenyl is well established,[27] but in the case of the **T1** ⇌ **N1** valence isomerization its π-acceptor property is more strongly pronounced since the **N2** product predominates over the **T2** product, while the reverse obtains in the unsubstituted cycloheptatriene.

Table V. Yields, Physical Constants, and Spectral Data of 4-Phenyl-1,2,4-triazoline-3,5-dione Adducts **3**



3



3'

	R	yield, %	physical constants, mp °C	^{1}H NMR ($CDCl_3$) type	no. of protons	δ, ppm	multiplicity[a]	J, Hz	IR ($CHCl_3$), cm^{-1} ν_{C-H}	ν_R	$\nu_{urazole}$
3a	CN	41	167–169 dec ($CHCl_3$)[b,f]	H_7	1	1.57–1.71	m		3030 m	2250 w	1780 m
				$H_{1,6}$	2	1.93–2.30	m				1720 s
				$H_{2,5}$	2	5.00–5.40	m				
				$H_{3,4}$	2	6.14	t′				
				N-Ph	5	7.10	s				
3a'	CN	50	206.5–207 dec ($CHCl_3$/ n-C_6H_{14})[b,f]	H_7	1	1.21	t	3.4	3040 w	2250 w	1770 m
				$H_{1,6}$	2	2.00–2.50	m				1715 s
				$H_{2,5}$	2	4.90–5.30	m				
				$H_{3,4}$	2	5.95	t′				
				N-Ph	5	7.15	s				
3b	CO_2Me	82	187[c] (MeOH)[f]	H_7	1	1.41	t	3.0		1730[d]	1770[d]
				$H_{1,6}$	2	2.19	m				
				OMe	3	3.67	s				
				$H_{2,5}$	2	5.23	m				
				$H_{3,4}$	2	6.15	t′				
				N-Ph	5	7.40	s				
3c	CHO	63	167–168[e,f]	H_7	1	1.55–1.75	m		3030 m	1700 s	1760 s
				$H_{1,6}$	2	2.10–2.40	m		3010 m		
				$H_{2,5}$	2	4.90–5.30	m		2845 m		
				$H_{3,4}$	2	5.95	t′		2720 m		
				N-Ph	5	7.15	s				
				CHO	1	9.00	d	3.8			
3d	OMe	75	147–148 (dec)[f]	$H_{1,6}$	2	1.65–1.90	m		3020 w	1150 s	1775 m
				H_7	1	2.67	t	1.4	2955 w		1713 s
				OMe	3	3.15	s		2920 w		
				$H_{2,5}$	2	4.85–5.20	m		2843 w		
				$H_{3,4}$	2	5.90	t′				
				N-Ph	5	7.10	s				
3e	Ph	92	189–190 (dec) (MeOH/ C_6H_6, 1:1)[f]	$H_{1,6,7}$	3	1.50–2.00	m		3070 w	1605 m	1770 m
				$H_{2,5}$	2	5.06	m		3050 w		1700 s
				$H_{3,4}$	2	5.96	m		3000 w		
				Ph	5	6.55–7.02	m		2980 w		
				N-Ph	5	7.15	s				

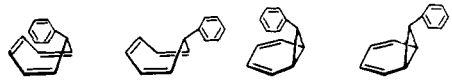
[a] Primed notation denotes second-order splitting. [b] PLC on silica gel, eluting with benzene/ethyl acetate (17:3), followed by recrystallization from chloroform. [c] Pikulik, I; Childs, R. F. *Can. J. Chem.* **1977**, *55*, 251. [d] KBr pellet. [e] Column chromatography on silica gel, eluting with $CHCl_3$/MeOH (49:1), followed by recrystallization from acetone. [f] Elemental analysis was within acceptable limits of 0.3% for C and 0.2% for H.

Although the qualitative trends of the 7-substituent on the **T1** ⇌ **N1** dynamic equilibrium are nicely monitored by the singlet oxygen dienophile in terms of the **T2** and **N2** (2 + 4)-cycloadducts, our product data are not sufficiently precise to warrant quantitative conclusions concerning the activation parameters for the **T1** ⇌ **N1** valence isomerization. Previously the activation free energy for this process has been bracketed between 2 and 12 kcal/mol, the lower limit for the dicyano derivative[22] and the upper limit for the unsubstituted cycloheptatriene.[23] Since the activation free energy for (2 + 4)-cycloaddition of singlet oxygen is ca. 6–8 kcal/mol[26] and lies within the range of $\Delta G^{\ddagger}$ values for the valence isomerization of cycloheptatriene, our qualitative product data do reflect realistically the perturbation of the 7 substituent on this dynamic equilibrium.

At first sight, the PTAD cycloaddition results, i.e., exclusive formation of the norcaradiene adduct **3**, seem puzzling since this excellent dienophile would be expected to arrest the **T1** ⇌ **N1** dynamic equilibrium. However, the activation parameters, i.e., $\Delta H^{\ddagger} \sim 8$–10 kcal/mol, $\Delta S^{\ddagger} \sim -31$ to -33 eu, and $\Delta G^{\ddagger}_{300K} \sim 17$–20 kcal/mol,[28] lie well beyond the range 2–12 kcal/mol for the activation free energy of the **T1** ⇌ **N1** valence isomerization. For every substituent examined here, the activation barrier for the **T1** ⇌ **N1** valence tautomerization is significantly lower than that for the cycloaddition of PTAD. Since the **N1** valence isomer is expected to react with PTAD significantly faster than **T1**, the **T1** ⇌ **N1** dynamic equilibrium is syphoned off exclusively through the norcaradiene adduct. Compared with singlet oxygen, PTAD is considerably more sluggish (by ca. 12 kcal/mol), and therefore more selective, in its dienophilic reactivity with cycloheptatriene. Viewed from this perspective, singlet oxygen appears to be the most powerful dienophile on hand. Consequently, singlet oxygen is a useful dienophile for probing dynamic valence tautomerization equilibria.

With respect to the ring inversion equilibria in cyclohepta-

triene (eq 1), only the cyano group proved useful since both the *exo*-**N2a** and *endo*-**N2a'** endoperoxide isomers were formed. All the other substituents, i.e., CO_2Me, CHO, OCH_3, and C_6H_5, gave exclusively the exo product, regardless whether it was tropilidene or norcaradiene derived. This can be adequately rationalized in terms of the steric factors of the 7 substituent. For example, a large group such as C_6H_5 will destabilize the endo conformations **T1e'** and **N1e'** relative to the respective exo conformations **T1e** and **N1e.** Thus, it is not



T1e' T1e N1e' N1e

surprising that only the endoperoxides **T2e** (3%) and **N2e** (61%) were formed on singlet oxygenation of cycloheptatriene **1e**.

For the small linear cyano group, conformations such as **T1a'** and **N1a'** are not as serious as for the bulky phenyl group. Indeed, appreciable amounts of the endo adducts **N2a'** and **N3a'** are formed between cycloheptatriene **1a** and $^1O_2$ and PTAD, i.e., the exo/endo ratios are 1.2 and 1.5, respectively. In fact, by low temperature ^1H NMR and ^{13}C NMR the energy difference between the conformations **T1a** and **T1a'** was estimated to be ca. 0.78 kcal/mol at −155 °C[21] and ca. 0.38 kcal/mol at −132.5 °C.[29] These findings corroborate quite nicely our cycloaddition results with $^1O_2$ and PTAD.

Experimental Section

All melting points and boiling points are uncorrected. Solvents and starting materials were purified according to standard literature procedures. The infrared spectra were recorded on a Perkin-Elmer Infracord Model 283 and the ^1H NMR spectra on a Hitachi Perkin-Elmer R-24 spectrometer. Elemental analyses were carried out by Atlantic Analytical Labs., Atlanta, Ga.

General Method for the Photooxygenation of 7-Substituted 1,3,5-Cycloheptatrienes 1. A CCl_4 solution of the cycloheptatriene **1** (2%) and tetraphenylporphyrin sensitizer (1 mg per 10 mL solution) at 0 °C was irradiated with a General Electric 400-W sodium street lamp while passing continuously a slow stream of dry oxygen gas. The progress of the photooxygenation was monitored by ^1H NMR until essentially complete consumption of the starting material. The solvent was rotoevaporated (26 °C at 16 mmHg) and the residue chromatographed on silica gel at 25 °C, eluting with CH_2Cl_2/C_5H_{12}. Final purification was achieved by recrystallization from the appropriate solvent or by fractional distillation. In the case of isomer mixtures, repetitive silica gel chromatography was essential for separating the isomers. The results are summarized in Table I.

Diimide Reduction of Endoperoxides 2 to the Bicyclic Peroxides 4. To a magnetically stirred suspension of dipotassium azodicarboxylate (5.0–140.0 mmol) and endoperoxide **2** (1.0 mmol) in 20 mL of CH_2Cl_2 at 0 °C was added dropwise a solution of glacial acetic acid (9.9–277.2 mmol) in 10–50 mL of CH_2Cl_2. After complete addition (45–60 min), the reaction mixture was stirred at 0 °C for an additional 30 min and then at ambient temperature until complete disappearance of the yellow color of the azodicarboxylate (ca. 5 h). The suspension was cooled again to 0 °C and 10–50 mL of H_2O added dropwise. The organic layer was separated, washed with H_2O (1 × 10 mL), 5% aqueous $NaHCO_3$ (1 × 10 mL), and again H_2O (2 × 10 mL), dried over anhydrous $MgSO_4$, the solvent rotoevaporated, and the product purified by recrystallization or fractional distillation at reduced pressure. The results are summarized in Table II.

Thermal Isomerization of Endoperoxides 2 into the Bisepoxides 5. A solution of the endoperoxides (0.5 mmol) in 2 mL of toluene was placed into a constricted Pyrex test tube, sealed under vacuum, and heated at 120–140 °C for 60–120 min. The solvent was rotoevaporated and the residue recrystallized from the appropriate solvent system. The results are collected in Table III.

Triphenylphosphine Deoxygenation of Endoperoxides 2 to the Epoxy Olefins 6. To a stirred solution of the endoperoxide **2** (0.25 mmol) in 0.5 mL of $CHCl_3$ at 0 °C was added the triphenylphosphine (0.25 mmol) in small portions over a period of 10 min. The mixture was allowed to warm up to room temperature, stirred for 30 min, and the solvent rotoevaporated. The residue was either chromatographed on silica gel, eluting with CH_2Cl_2/C_5H_{12}, or fractionally distilled. Final purification was achieved by either recrystallization or sublimation at reduced pressure. The results are given in Table IV.

Cycloaddition of 4-Phenyl-1,2,4-triazoline-3,5-dione (PTAD) to 7-Substituted 1,3,5-Cycloheptatrienes 1. To a stirred solution of the cycloheptatriene **1** (1.0–2.5 mmol) in 10 mL of dry, ethanol-free $CHCl_3$ was added at 0 °C in small portions the PTAD (1.0–2.5 mmol) over a period of 15 min. After stirring at 0 °C for an additional 10 min, the mixture was warmed up to room temperature and stirred for 30 min. The solvent was rotoevaporated and the solid residue recrystallized from the appropriate solvent. When recrystallization proved cumbersome, the urazole **3** was first chromatographed on silica gel, eluting with $CHCl_3$/MeOH (98:2) or PhH/EtOAc (17:3). The results are summarized in Table V.

Acknowledgments are made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, the National Science Foundation (Grant No. 78-12621), and the National Institutes of Health (GM-00141-04 and RR-8102-07) for financial support.

References and Notes

(1) Paper No. 88 in the Cyclic Peroxide Series.
(2) NIH Career Development Awardee, 1975–1980.
(3) Maier, G. *Angew. Chem.* **1967,** *79,* 446.
(4) (a) Conrow, K.; Howden, M. E.; Davis, D. *J. Am. Chem. Soc.* **1963,** *85,* 1929. (b) Heyd, W. E.; Cupas, C. A. *Ibid.* **1969,** *91,* 1559.
(5) (a) Berson, J. A.; Willcott, M. R. *J. Am. Chem. Soc.* **1966,** *88,* 1494. (b) Görlitz, M.; Günther, H. *Tetrahedron* **1969,** *25,* 4467. (c) Reich, H. J.; Ciganek, E.; Roberts, J. D. *J. Am. Chem. Soc.* **1970,** *92,* 5166.
(6) We shall use the capital letters T and N to designate tropilidene and norcaradiene isomers, the prime (') to denote exo and endo isomers, the arabic numerals 2, 3, 4, 5, and 6 to describe the derivatives of cycloheptatriene **1**, and the small letters a, b, c, d, and e to indicate the type of 7 substituent.
(7) (a) Günther, A.; Gorlitz, M.; Hinrichs, H. *Tetrahedron* **1968,** *24,* 5665. (b) Günther, H. *Z. Naturforsch. B.* **1969,** *24,* 680.
(8) (a) Hoffmann, R. *Tetrahedron Lett.* **1970,** 2907. (b) Günther, H. *Ibid.* **1970,** 5173.
(9) Adam, W.; Balci, M. *J. Org. Chem.* **1979,** *44,* 1189.
(10) von E. Doering, W.; Knox, L. H. *J. Am. Chem. Soc.* **1957,** *79,* 352.
(11) von E. Doering, W.; Knox, L. H. *J. Am. Chem. Soc.* **1954,** *76,* 3203.
(12) Betz, W.; Daub, J. *Chem. Ber.* **1972,** *105,* 1778.
(13) Jutz, C.; Voihenleither, F. *Chem. Ber.* **1964,** *97,* 29.
(14) (a) Grigg, R.; Hayes, R.; Sweeney, A. *J. Chem. Soc., Chem. Commun.* **1971,** 1248. (b) Strukul, G.; Viglino, P.; Ros, R.; Graziani, M. *J. Organomet. Chem.* **1974,** *74,* 307. (c) Günther, H.; Balci, M. Unpublished results.
(15) Adam, W.; Eggelte, H. J. *J. Org. Chem.* **1977,** *42,* 3987.
(16) Pachler, K. G. R. *Tetrahedron* **1971,** *27,* 187.
(17) Tori, K.; Komeno, T.; Nakagawa, T. *J. Org. Chem.* **1964,** *29,* 1136.
(18) Adam, W.; Balci, M. *Angew. Chem.* **1978,** *90,* 1014.
(19) Hoffmann, R.; Stohrer, W.-D. *J. Am. Chem. Soc.* **1971,** *93,* 6941.
(20) (a) Anet, F. A. L. *J. Am. Chem. Soc.* **1964,** *86,* 458. (b) Jensen, F. R.; Smith, L. A. *Ibid.* **1964,** *86,* 956.
(21) Günther, H.; Wehner, R. *J. Am. Chem. Soc.* **1975,** *97,* 923.
(22) (a) Reich, H. J.; Ciganek, E.; Roberts, J. D. *J. Am. Chem. Soc.* **1970,** *92,* 5166. (b) Hall, G. E.; Roberts, J. D. *Ibid.* **1971,** *93,* 2203. (c) Ciganek, E. *Ibid.* **1971,** *93,* 2207.
(23) (a) Klump, K. N.; Chesick, J. P. *J. Am. Chem. Soc.* **1963,** *85,* 130. (b) Berson, J. A.; Wilcott, M. R. *Ibid.* **1966,** *88,* 1494. (c) Görlitz, M.; Günther, H. *Tetrahedron* **1969,** *25,* 4467.
(24) (a) Paquette, L. A.; Volz, W. E. *J. Am. Chem. Soc.* **1976,** *98,* 2910. (b) Paquette, L. A.; Volz, W. E.; Beno, M. A.; Christoph. G. G. *Ibid.* **1975,** *97,* 2562. (c) James, D. R.; Birnberg, G. H.; Paquette, L. A. *Ibid.* **1974,** *96,* 7465.
(25) Tufariello, J. J.; Chang, J. H.; Bayer, A. C. *J. Am. Chem. Soc.* **1979,** *101,* 3315.
(26) Gorman, A. A.; Lovering, G.; Rodgers, M. A. J. *J. Am. Chem. Soc.* **1979,** *101,* 3050.
(27) (a) Cupas, C. A.; Comisarow, M. B.; Olah, G. A. *J. Am. Chem. Soc.* **1966,** *88,* 361. (b) Russel, G. A. *Ibid.* **1959,** *81,* 2017.
(28) (a) Burrage, M. E.; Cookson, R. C.; Gupta, S. S.; Stevens, I. D. R. *J. Chem. Soc., Perkin Trans. 2,* **1975,** 1325. (b) Cookson, R. C.; Gilani, H. S. S.; Stevens, I. D. R. *Tetrahedron Lett.* **1962,** 615.
(29) Bushweller, C. H.; Sharpe, M.; Weininger, S. J. *Tetrahedron Lett.* **1970,** 453.