

A Novel Oxygen-catalysed *trans*-*cis* Thermal Isomerization of *trans*-Cycloheptene

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Contrary to the efficient unimolecular decay to the *cis*-isomer under an atmosphere of nitrogen, *trans*-cycloheptene, prepared photochemically *in situ* at low temperature, underwent second-order *trans*-*cis* thermal isomerization under an atmosphere of air without giving any oxidation products. The rate constants and activation parameters are reported for this unique isomerization reaction. Following discussion of the role of oxygen in the isomerization process we propose a mechanism involving termolecular interaction between triplet oxygen and two molecules of the strained cycloalkene.

Recently we reported some aspects of the chemistry of *trans*-cycloheptene (**1t**) prepared photochemically at a low temperature.¹ *trans*-Cycloheptene, though highly constrained, with a calculated strain energy of *ca.* 27 kcal mol⁻¹,² is totally stable at -78 °C but isomerizes quantitatively to the *cis*-isomer (**1c**) on warming; the lifetimes determined by chemical trapping with acidic methanol are several minutes to 1 h at +1 to -15 °C.^{1b} This thermal *trans*-*cis* isomerization process is first order in *trans*-cycloheptene under an atmosphere of nitrogen. In an experiment to measure the lifetime, we accidentally carried out the chemical trapping procedure under an atmosphere of air, instead of nitrogen. The decay profile did not then fit first-order but followed second-order kinetics with respect to (**1t**). In this paper we report the novel second-order *trans*-*cis* thermal isomerization of the strained alkene, *trans*-cycloheptene, and discuss the role of the oxygen molecule in the isomerization process.

Results

trans-Cycloheptene (**1t**) was prepared *in situ* from the *cis*-isomer (**1c**) in a photosensitized *cis*-*trans* isomerization according to the procedure described previously.^{1b} A neutral methanol solution containing (**1c**) (0.01M), methyl benzoate (0.01M), and cyclo-octane (0.005M), as an internal standard, was irradiated at -78 °C under an atmosphere of nitrogen (Scheme 1). The irradiated solution, containing (**1t**) along with the unreacted (**1c**), the sensitizer, and cyclo-octane, was divided into several portions at this temperature under air, each of which was in turn immersed in a bath maintained at a desired temperature in the range -20 to -5 °C for varying periods of time. The subsequent addition of pre-cooled acidic methanol to the treated solutions and gradual warming to room temperature gave the methanol adduct (**2**) in yields varying with the treatment period.

Contrary to the thermal isomerization under nitrogen reported previously,¹ a plot of ln[(**2**)] as a function of time failed to give a straight line. Instead, a plot of 1/[(**2**)] versus time gave a good linear relationship at each temperature, indicating bimolecular decay of (**1t**) to (**1c**) under air. Similar experiments were repeated under oxygen to afford comparable results. Table 1 shows the second-order rate constants obtained for the thermal *trans*-*cis* isomerization of (**1t**) at various temperatures. A set of activation parameters for the thermal isomerization was obtained from the Arrhenius plot (*r* = 0.996), shown in the Figure, and from a plot of ln(*k*/T) versus 1/T; these parameters under air are shown in Table 2 along with those for the first-order isomerization under nitrogen.

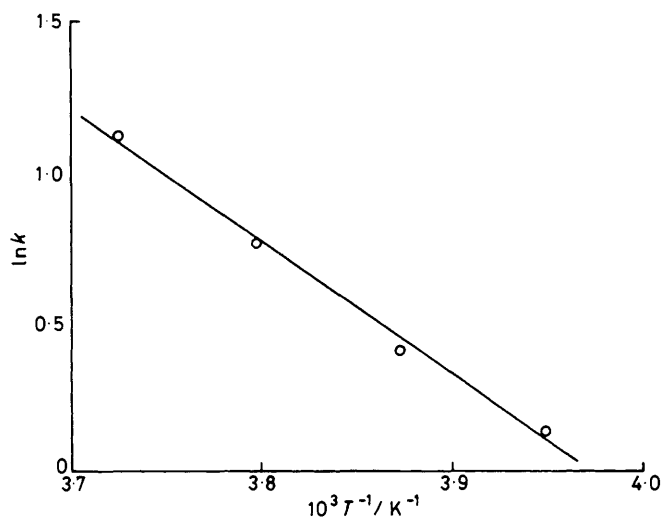
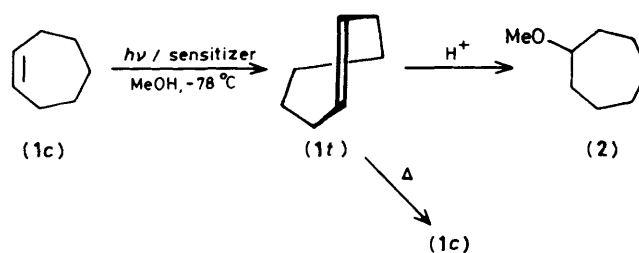


Figure 1. Arrhenius plot for second-order *trans*-*cis* isomerization of *trans*-cycloheptene (**1t**) under an atmosphere of air.

Several experiments were run under a variety of conditions in order to elucidate the fate of *trans*-cycloheptene under oxygen, as well as nitrogen. The results are shown in Table 3. Careful analyses of the reaction mixture by g.l.c. at a higher temperature revealed that small amounts (*ca.* 2%) of cyclodimers (**3**) and 1:1 cross-adducts (**4**) with the sensitizer^{1a} were produced in addition to the methanol adduct (**2**). Although the complete characterization of these minor products could not be made due to the low yields, the g.l.c.-m.s. analyses and the chemical behaviour upon hydrogenation over Pd-C of products (**3**) and (**4**) indicated that (**3**), *m/e* 192, is a mixture of two stereoisomeric cyclodimers, both of which are not hydrogenated over Pd-C, and that the cross-adducts (**4**), *m/e* 232, are composed of 1,3-

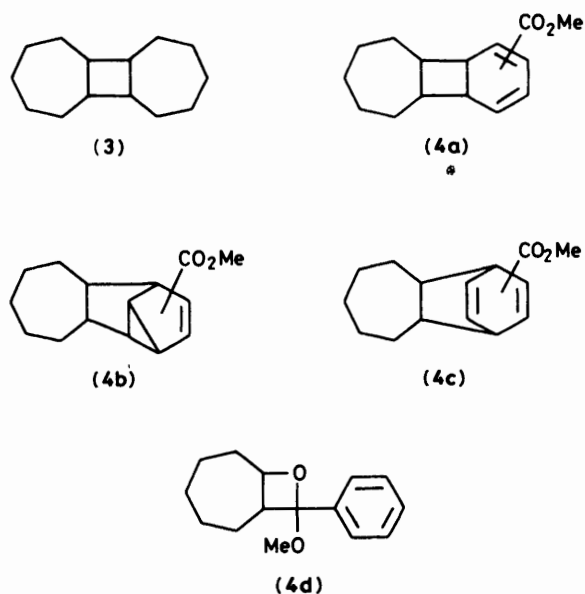
Table 1. Second-order rate constants ($M^{-1} s^{-1}$) for thermal *trans-cis* isomerization of *trans*-cycloheptene (*1t*) under air and oxygen

Temperature ($^{\circ}C$)	Atmosphere	
	Air	Oxygen
-5.0 ± 0.1	3.20 ± 0.03	
-10.0 ± 0.1	2.14 ± 0.05	1.99 ± 0.05
-15.0 ± 0.1	1.50 ± 0.04	1.44 ± 0.05
-20.0 ± 0.1	1.15 ± 0.02	

Table 2. Activation parameters for thermal *trans-cis* isomerization of *trans*-cycloheptene (*1t*) under nitrogen and air

Parameter ^a	Atmosphere	
	Nitrogen ^b	Air ^c
$E_a/kcal\ mol^{-1}$	17.4 ± 0.7	9.0 ± 0.6
$\log A$	11.1 ± 0.6	7.8 ± 0.5
$\Delta G_{260}^{\ddagger}/kcal\ mol^{-1}$	19.3 ± 1.4	14.9 ± 1.1
$\Delta H_{260}^{\ddagger}/kcal\ mol^{-1}$	16.9 ± 0.7	8.5 ± 0.6
$\Delta S_{260}^{\ddagger}/cal\ mol^{-1}\ K^{-1}$	-9 ± 8	-25 ± 7

^a 1 kcal = 4.18 kJ. ^b First order; reference 1. ^c Second order; this work.



adduct(s) (4b),* 1,2- and/or 1,4-adducts (4a and c), and oxetane (4d), which can be distinguished from one another by the g.l.c.-m.s. analyses of the mixture before and after the hydrogenation.

Search for the oxidation products of (1) was made with the reaction mixture treated under an atmosphere of air. On comparison with the g.l.c. retention times of the authentic specimens synthesized independently, it was revealed, however, that neither 1,2-epoxycycloheptane (5) nor 3-hydroperoxycycloheptene (6)† was produced in a detectable yield (0.1%)

* The photochemical reaction of (1c) sensitized by *p*-xylene produces similar 1,3-cross-adducts as major products; P. J. Kropp, J. J. Snyder, P. C. Rawlings, and H. G. Fravel, Jr., *J. Org. Chem.*, 1980, **45**, 4471.

† This compound synthesized independently decomposes on injection into the gas chromatograph, giving cyclohept-2-en-1-ol and cyclohept-2-en-1-one as significant peaks in a ca. 1:1 ratio, so that the absence of (6) was confirmed by the absence of the decomposition products on the gas chromatogram.

even under oxygen. The thermal *trans-cis* isomerization of (1t) under oxygen was also performed in the presence of 2,3-dimethylbut-2-ene (1M) added as a trapping agent for singlet molecular oxygen, but no oxygenation of the butene affording 3-hydroperoxy-2,3-dimethylbut-1-ene was observed.

Discussion

Interestingly the introduction of air in place of nitrogen dramatically alters the isomerization mechanism of *trans*-cycloheptene. In sharp contrast to the first-order decay under nitrogen, in the presence of air *trans*-cycloheptene (1t) isomerizes thermally to the *cis*-isomer (1c) through a second-order decay process. However, when oxygen is used instead of air it no longer has any further significant effect on the mechanism or on the rate constants, as shown in Table 1. This is probably due to the higher concentration of oxygen even in air-saturated methanol than that of the (1t) generated *in situ*; $[O_2]$ in air- and oxygen-saturated methanol at 0 to $-25^{\circ}C$ is 2.6 and 13mm,³ respectively, and [(1t)] prepared photochemically is less than 1.5mm. It is suggested therefore that only those oxygen molecules which are in interaction with (1t) play a significant role in altering the mechanism of the isomerization process, the other oxygen molecules not affecting the process.

The activation parameters change drastically depending on the atmosphere employed. As can be seen from Table 2, both the activation energy and frequency factor for the isomerization of (1t) under air are much smaller than those obtained under nitrogen. In particular the considerably negative entropy of activation should be noted and may be a consequence of some molecular association at the transition state, which facilitates the *trans-cis* isomerization of (1t) in the presence of oxygen.

Table 3 shows the chemical consequence of a series of treatments of (1t) under a variety of conditions. The results indicate the following. 1. The cross-adducts (4) are produced only in the photochemical process, since in runs 1—9 their yields are not affected by the subsequent treatments after the irradiation. 2. The cyclodimers (3), although in negligible yields, are produced from (1t) not in the photochemical but in the thermal process, since the formation of (3) is efficiently quenched by the immediate addition of acidic methanol to the irradiated solution at $-78^{\circ}C$ as shown in runs 3 and 5. 3. Except for the minor cyclodimerization process, the *trans*-isomer (1t) thermally isomerizes exclusively to the *cis*-isomer (1c) without giving rise to any additional product even in the presence of oxygen, since the total recoveries are comparable for runs 1—9. It is therefore obvious that in the presence of oxygen the *trans*-isomer (1t) undergoes oxygen-catalysed bimolecular isomerization to give the *cis*-isomer (1c).

There may be three possible mechanisms that could rationalize the oxygen participation in the isomerization process. They are: (i) autoxidation; (ii) reversible addition-elimination of oxygen; and (iii) charge-transfer complex formation between (1t) and oxygen.

The autoxidation mechanism may seem most plausible, since the *cis*-isomer (1c) has been reported to be readily oxidized under oxygen at 60—80 $^{\circ}C$ even in the absence of an initiator⁴ and the *trans*-isomer (1t) is more activated than (1c). Moreover, it has been shown that, on autoxidation of tetralin and indene, the rate of initiation obeys a second-order expression with respect to the substrate.⁵ However, this possibility is clearly ruled out by the facts that 1,2-epoxycycloheptane (5) or 3-hydroperoxycycloheptene (6), formation of which is characteristic of autoxidation,⁴ was not detected by gas chromatography, and the total recoveries under nitrogen and oxygen are comparable with each other, as shown in Table 3.

The addition of oxygen to the strained double bond of (1t), giving rise to a 1,4-diradical, and the subsequent detachment of

Table 3. Chemistry under a variety of conditions of *trans*-cycloheptene (**1t**) prepared photochemically *in situ* at -78°C

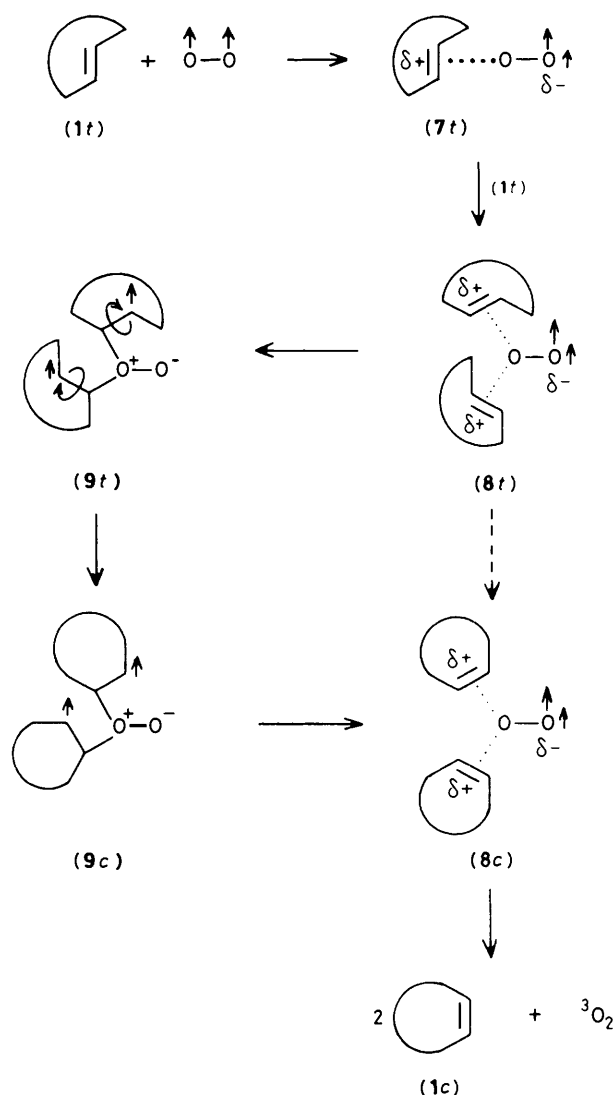
Run	Condition ^a			Treatment ^b	Yield (%) ^c				Total recovery ^d (%)
	Temperature ($^{\circ}\text{C}$)	Time (min)	Atmosphere		(1c)	(2)	(3)	(4)	
1	-78	5	N_2	i	90	<0.1	0.6	2.2	93
2				i → ii	91	0.2	0.6	2.1	94
3				ii → i	75	13.4	<0.1	2.0	91
4	-10	120	O_2	i → ii	87	<0.1	0.5	2.2	90
5				ii → i	74	13.1	<0.1	1.9	89
6				i → ii	91	0.2	0.5	2.1	94
7	O_2			ii → i	92	0.8	0.5	2.0	95
8				i → ii	89	0.2	0.5	2.3	92
9				ii → i	86	0.6	0.4	2.1	90

^a The irradiated solution was divided into several portions at -78°C , each of which was kept at the stated temperature for the stated period under the atmosphere indicated. ^b The following treatments were made after standing under the specific conditions mentioned above: (i) the solution was warmed gradually to room temperature; (ii) pre-cooled acidic methanol was added to the solution. ^c Yield based on (1c) used. ^d Combined yield of (1c), (2), (3) (doubled), and (4).

oxygen after the bond rotation about the former double bond may afford the *cis*-isomer (1c) and oxygen, without loss of the total recovery. This simple addition-elimination mechanism, whilst being attractive, is not consistent with the second-order decay of (1t).

Recently the intervention of singlet oxygen or its chemically equivalent complex has been proposed in the triplet oxygenation of some electron-rich alkenes or strained alkynes with ground-state oxygen.⁶ Of these the triplet oxygenation of the strained cycloalkyne, 3,3,7,7-tetramethyl-5-thiacycloheptyne,^{6a} is of special interest to us. It has been suggested that this reaction may be initiated by the charge-transfer (C.T.) interaction between the constrained π -bond and molecular oxygen, which on spin flip leads to the formation of a singlet complex and/or singlet oxygen, which in turn gives rise to the chemiluminescent dioxetene intermediate.

trans-Cycloheptene (1t) is also highly strained.² In this context we first suspected that a similar interaction between (1t) and triplet oxygen might produce singlet oxygen *via* spin flip, as is the case with the triplet oxygenation of thiacycloheptyne.^{6a} But no oxygenation products of (1t) or 2,3-dimethylbut-2-ene added as a trapping agent for singlet oxygen were detected in the reaction mixture. This, however, does not necessarily exclude the possibility of the C.T. interaction itself. The C.T. interaction is presumed in view of the substantially low ionization potential (IP) of (1t) of around 8.2 eV.* Although it is not necessarily clear why two molecules of (1t) are required to effect the oxygen-catalysed *trans*-*cis* isomerization, in order to rationalize all the results obtained in this work we tentatively propose the termolecular C.T. interaction mechanism, shown in Scheme 2, for the second-order decay of the highly strained (1t) to (1c) in the presence of oxygen without any loss of total recovery. Unlike the feasible spin flip in the collision complex of the thiacycloheptyne with triplet oxygen,^{6a} in the present



mechanism the initial collision complex (7t) does not suffer spin flip but gives a 2:1 C.T. complex (8t), in which a simultaneous *trans*-*cis* isomerization process takes place *via* zwitterionic

* The adiabatic IP (8.53 eV) of the next higher homologue, *trans*-cyclo-octene, is lower than that of *cis*-cyclo-octene by 0.29 eV, which is 73% of the strain-energy difference (0.40 eV) between both isomers. Then the IP of (1t) is roughly evaluated by subtracting 73% of the strain-energy difference (0.87 eV)² between (1t) and (1c) from the IP (8.87 eV) of (1c). This fairly low IP of a mono-olefin is comparable with those of 2,3-dimethylbut-2-ene (8.30 eV) and cyclopentadiene (8.20 eV), but is not so low to permit full electron-transfer, affording a radical cation (1)⁺ and superoxide anion O₂⁻. (Strain energies quoted from R. B. Turner and W. R. Meador, *J. Am. Chem. Soc.*, 1957, 79, 4133; reference 2. IP data quoted from C. Batich, O. Ermer, E. Heilbronner, and J. R. Wiseman, *Angew. Chem.*, 1973, 85, 302; P. Bischof and E. Heilbronner, *Helv. Chim. Acta*, 1970, 53, 1677.)

intermediates (9) with full C—O bond formation. The resulting less favourable 2:1 complex (8c) immediately dissociates to give (1c) and the regenerated triplet oxygen.

Although the full C—O bond formation and the consequent intervention of the 2:1 complexes (9) have no experimental support and would be somewhat questionable, it is still less likely that the reduced bond order, coupled with the strain, of the *trans*-double bond facilitates bond rotation in (8t) affording (8c) directly (dashed line in Scheme 2). The smaller activation energy under an atmosphere of air (Table 2) may be attributable to the reduced bond order.

Experimental

General.—Purification procedures for the commercially available materials and the g.l.c. analyses conditions for (1c) and (2) have been described previously.^{1b} Mass spectra were recorded with 15 eV bombardment using a Hitachi 0-63-RM-50 g.l.c.—mass spectrometer combination.

Low-temperature irradiations were performed with a 300 W high-pressure mercury lamp in a 'dry ice'-methanol bath through a transparent quartz Dewar vessel. A temperature-controlled methanol bath (± 0.1 °C) was used in the kinetic studies. Treatments after irradiation were described in the test and in Table 3.

Identifications.—In addition to the previously reported methoxycycloheptane (2), small amounts of cyclodimers (3) and 1:1 cross-adducts (4) of cycloheptene with the sensitizer, methyl benzoate, were detected by g.l.c. and characterized as a mixture by g.l.c.—m.s. G.l.c. analyses were conducted with these minor products on a 1 m column of 3% SE-30 and a 75 cm column of a 4:1 mixture of 10% Apiezon L and 10% PEG-20M, which showed that the cyclodimers (3) are composed of two isomers in a ratio of *ca.* 1:3, and the cross-adducts (4) of at least four isomers in a ratio of *ca.* 1:4:4:2. G.l.c. retention times over the Apiezon plus PEG-20M column at 180 °C were: (2), 0.4; methyl benzoate, 0.7; two isomers of (3), 4.1 and 4.8; four isomers of (4), 6.9, 10.1, 10.7, and 12.7 min; those over the SE-30 column at 180 °C were: (3), 1.7 and 2.0; (4), 3.3, 4.5, 5.6, and 7.2 min.

Owing to the limitation of the quantity of the sample available, the structures of (3) and (4) rest only on the mass spectra and chemical behaviours on hydrogenation over Pd—C. Two cyclodimers of (3) gave somewhat different m.s. fragmentation patterns with the same molecular ion peak at *m/e* 192 and base peak at *m/e* 96; *m/e* (relative intensities for two isomers in parentheses) 192 (8, 7%), 134 (11, <10), 111 (17, 14), 110 (18, 11), 109 (19, <10), 97 (60, 36), 96 (100, 100), 95 (28, 22), 92 (36, <10), 91 (31, <10), 82 (34, 23), 81 (66, 51), 68 (25, 22), 67 (50, 38). From comparisons of the m.s. fragmentation patterns, under the same m.s. conditions, with the four well assigned cyclohexene dimers,* it is obvious that the two cycloheptene dimers (3) are higher homologues of the cyclohexene dimers, although their stereochemistries are not known. On hydrogenation of (3) in pentane for 1 h over 5% Pd—C at a hydrogen pressure of 1 atm, no change in g.l.c. retention time or m.s. fragmentation pattern was observed, proving the absence of a double bond in (3).

* The assignment of three out of four cyclohexene dimers produced in the photosensitization of cyclohexene has been reported: R. G. Salomon, K. Foltz, W. E. Streib, and J. K. Kochi, *J. Am. Chem. Soc.*, 1974, **96**, 1145. We isolated the remainder, *i.e.*, the last peak on g.l.c. over a PEG-20M column, from the reaction mixture obtained in a *p*-xylene photosensitization of cyclohexene. Full assignment of this *trans-syn-trans* isomer, m.p. 83.7—84.0 °C, was made by means of i.r., ¹H and ¹³C n.m.r., and mass spectra. Details will be reported elsewhere.

Of four cross-adducts (4), the first three, in the order of g.l.c. retention times, have quite similar m.s. fragmentation patterns, but the last one has a completely different pattern: *m/e* (relative intensities for four isomers in parentheses) 232 (7, 6, 4, 82%), 173 (27, 27, 10, 100), 172 (<10, <10, <10, 43), 150 (<10, <10, <10, 35), 137 (100, 100, 100, 30), 131 (<10, <10, <10, 36), 117 (<10, <10, <10, 34), 105 (34, 34, 15, 28), 96 (40, 40, 24, 13), 91 (<10, <10, <10, 66), 81 (58, 59, 44, 38), 68 (44, 42, 30, 13), 67 (73, 75, 59, 46), 55 (25, 28, 12, 21), 54 (30, 32, 29, 21). Hydrogenation of (4) over Pd—C gave a complex mixture which showed seven g.l.c. peaks at 3.5, 4.1, 4.5, 5.2, 5.9, 6.3, and 7.2 min on an SE-30 column under the same conditions mentioned above. G.l.c.—m.s. analysis of the hydrogenated mixture revealed that the first six products have increased molecular weights of 234 or 236, and the last one is not hydrogenated but has the same retention time and fragmentation pattern as those before hydrogenation. These results suggest that the unreduced isomer is the oxetane (4d) and the hydrogenated ones are a mixture of stereo- and regio-isomers of 1,2-, 1,3-, and/or 1,4-adducts (4a—c), although the assignments are not conclusive at present.

Authentic Specimens.—1,2-Epoxycycloheptane (5) was synthesized by stirring (1c) (0.016 mol) with *m*-chloroperbenzoic acid (0.017 mol) for 12 h in dichloromethane (50 ml) at room temperature. Work-up gave the oxirane (5) in 36% yield: b.p. 71 °C at 33 Torr; *m/e* 112; ν_{\max} . 2 925, 2 850, 1 460, 1 250, 1 100 cm^{-1} ; ¹H n.m.r. (CCl₄, Me₄Si as an internal standard) δ 2.9 (m, 2-H), 1.9 (m, 4-H), 1.5 (m, 6-H); ¹³C n.m.r.⁷ (neat, Me₄Si) δ 56.0 (d), 32.3 (t), 30.1 (t), 25.5 (t).

3-Hydroperoxycycloheptene (6) was synthesized by the Methylene Blue (2×10^{-3} M)-sensitized photo-oxygenation of (1c) (0.01 mol) in chloroform (40 ml) at 0 °C with continuous bubbling of oxygen. After 15 h irradiation by a 60 W tungsten lamp, 80% of (1c) was consumed. Work-up gave the hydroperoxide (6) in *ca.* 60% yield; ν_{\max} . 3 370, 3 030, 2 930, 2 860, 1 655, 1 450, 1 335, 830, 680 cm^{-1} ; ¹H n.m.r. (CCl₄, Me₄Si) δ 5.7 (m, 2-H), 4.5 (br s, 1-H), 3.6 (m, 1-H), 1.3—2.2 (m, 8-H). On injection into the g.c. the hydroperoxide (6) gave two peaks corresponding to cyclohept-2-en-1-one, *m/e* 110, and cyclohept-2-en-1-ol, *m/e* 112. NaBH₄ reduction of (6) in methanol gave cyclohept-2-en-1-ol in 84% yield: *m/e* 112; ν_{\max} . 3 350, 2 930, 2 850, 1 650, 1 400, 680 cm^{-1} ; ¹H n.m.r. (CCl₄, Me₄Si) δ 5.6 (m, 2-H), 4.4 (br s, 1-H), 3.4 (m, 1-H), 1.4—2.2 (m, 8-H).

Acknowledgements

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