Synthesis of 1-Substituted *cis*-Bicyclo[4.2.0]octanones through [2 + 2] Cycloadditions of Dichloroketene to Alkenes. Structural Characterization of Cycloadducts by Oxa-Ring Expansion[1]

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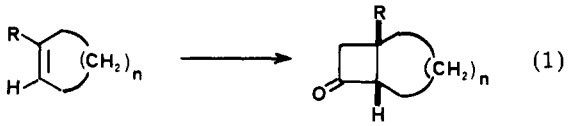
The [2 + 2] cycloaddition of dichloroketene to a series of 1-substituted cyclohexenes is shown to proceed in a highly regio- and stereospecific manner. The structures of the cycloadducts were determined by reductive dechlorination to the cyclobutanones, and the structures and stereochemistry of the latter as *cis*-bicyclo[4.2.0]octan-7-ones (4) were established by an oxa-ring expansion to the corresponding *cis*-octahydrobenzo[*b*]furan-2-ones (6). The structures of the lactones 6 were established by ^1H and ^{13}C NMR studies which further indicated that these compounds exist in conformation **6a** rather than **6b**. The success of the regio- and stereospecific cycloaddition of dichloroketene to the 1-substituted cyclohexenes discussed is found to be critically dependent on utilizing the zinc dehalogenation procedure for its in situ generation. Additional examples of the [2 + 2] cycloaddition of dichloroketene to indene, 1,4-dihydronapthalene and 1,2-dihydronaphthalene is also presented.

There has been considerable effort in recent years directed to the synthesis of *Sceletium* alkaloids. This not only has culminated in successful syntheses of alkaloids of this family representing different structural types but also has led to the development of new synthetic methodology.[2]

We have undertaken an independent investigation designed to provide a general synthetic approach to *Sceletium* bases of the mesembrine[3] and joubertiamine[4] subgroups. As a first stage in the development of a facile and efficient synthesis of these alkaloids[5,6] we required compounds represented by the general structure 1 (see Scheme I).

Regiospecific [2 + 2] Cycloadditions

In 1973 we reported[7] in a preliminary communication the first examples of [2 + 2] cycloadditions of trisubstituted alkenes with dichloroketene. The reactions involved the conversion of a series of 1-substituted cyclohexenes and 1-methylcyclopentene to the 2,2-dichlorocyclobutanones shown in eq 1. The full details of this work, including

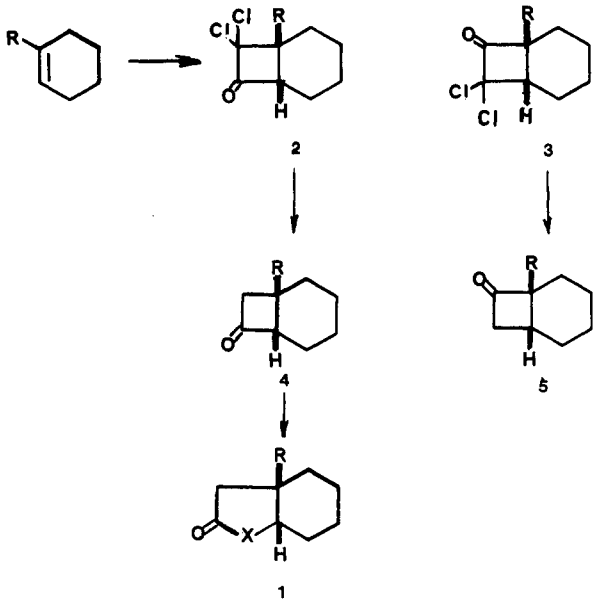


(1)

proof of the structures of the cycloadducts, are described together with further extensions of the original study in the sequel of this paper.

A most important feature of this study was the finding that the success of the reaction was critically dependent upon employing the zinc dehalogenation method to generate dichloroketene. Attempts to effect the cycloaddition reaction with 1-methyl- and 1-phenylcyclohexene were unsuccessful when the dichloroketene was generated in situ by dehydrohalogenation of dichloroacetyl bromide. The

Scheme I



reactivity difference of dichloroketene generated by the two methods had been noted previously with simple ketenes[8] and in two examples[9] with disubstituted alkenes. Following our original disclosure of this method for effective cycloadditions to trisubstituted alkenes, two recent reports[10,11] have both focused on experimental modifications relating to the use of the zinc dechlorination procedure for generating dichloroketene in order to obtain improved yields of cycloaddition with less reactive alkenes.

In contrast to the failure to effect cycloaddition of dichloroketene to 1-phenylcyclohexene when the dehydrohalogenation procedure was employed, an ethereal solution of 1-phenylcyclohexene reacted readily with trichloroacetyl bromide in the presence of activated zinc to afford a crude product which showed one major (89%) component on gas chromatography. The IR spectrum of this product contained a strong carbonyl band at 1805 cm^{-1} in accord with that expected for a cyclobutanone of structure **2** (R = Ph) or **3** (R = Ph). Reductive dechlorination of the crude

(1) This paper is part 11 in the series "Sceletium Alkaloids". For part 10 see: Jeffs, P. W.; Capps, T. A.; Redfearn, R., submitted for publication in *J. Org. Chem.*

(2) For recent examples see: Martin, S. F.; Puckette, T. A.; Colapret, J. A.; *J. Org. Chem.* **1979**, *44*, 3391. Sanchez, I. H.; Tallabs, F. R. *Chem. Lett.* **1981**, 891. Takano, S.; Imamura, Y.; Ogasawara, R. *Tetrahedron Lett.* **1981**, 4479.

(3) Jeffs, P. W.; Hawks, R. L.; Farrier, D. S. *J. Am. Chem.* **1969**, *91*, 3831.

(4) Arndt, R. R.; Kruger, P. E. J. *Tetrahedron Lett.* **1970**, 3237.

(5) Jeffs, P. W.; Molina, G.; Cortese, N. A.; Hauck, P. R.; Wolfram, J. *J. Org. Chem.*, following paper in this issue.

(6) Jeffs, P. W.; Cortese, N. A.; Wolfram, J., *J. Org. Chem.*, following paper in this issue.

(7) Jeffs, P. W.; Molina, G. *J. Chem. Soc., Chem. Commun.* **1973**, 3.

(8) Brady, W. T.; Patel, A. *J. Heterocycl. Chem.* **1971**, *8*, 739.

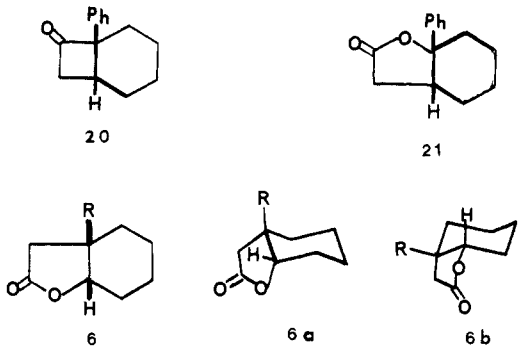
(9) (a) Fletcher, V. R.; Hassner, A. *Tetrahedron Lett.* **1970**, 1071. (b) Hassner, A.; Fletcher, V. R.; Harmon, D. P. G. *J. Am. Chem. Soc.* **1971**, *93*, 264.

(10) Krepski, L. R.; Hassner, A. *J. Org. Chem.* **1978**, *43*, 2879.

(11) Bak, D. A.; Brady, W. T. *J. Org. Chem.* **1979**, *44*, 107.

0022-3263/82/1947-3871$01.25/0

Chart I



product could be effected with zinc and acetic acid or preferably by the Corey procedure employing zinc–methanol–ammonium chloride, and the product **4** (R = Ph) was obtained in yields which varied from 30% to 70%. The yields in the 50–70% range were all obtained by using the latter reductive dechlorination procedure.

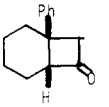
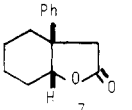
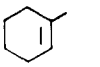
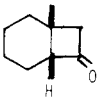
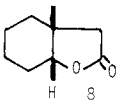
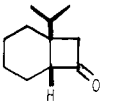
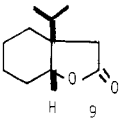
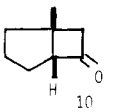
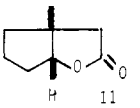
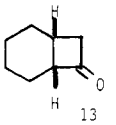
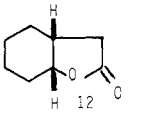
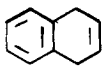
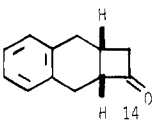
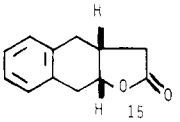
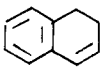
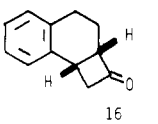
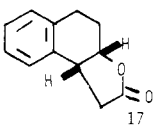
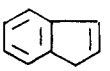
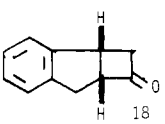
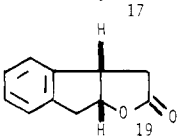
The structure of the cycloaddition product as **4** (R = Ph) rather than as **5** (R = Ph) was established by subjecting the dechlorinated cyclobutanone (ν_{CO} 1765 cm^{-1}) to a Baeyer–Villiger oxidation. The ^1H NMR spectrum of the lactone product from this reaction contained a low-field 1-H triplet at δ 4.90 which indicated that the ring juncture containing the lactone ether oxygen is attached to a carbon bearing a proton in accord with structure **6** (R = Ph). The cis stereochemistry of the ring fusion in the lactone followed from the apparent couplings ($J \approx 3.0$ Hz) of the 7a-proton at δ 4.90 (vide infra).

Supporting evidence for the structure of the lactone **6** (R = Ph) was obtained by the synthesis of the regioisomer **21** by a Baeyer–Villiger oxidation of the known 1-phenylbicyclo[4.2.0]octan-8-one (**20**[12], Chart I). A comparison of the ^1H and ^{13}C NMR spectral properties (Table II) of the two lactones **6** (R = Ph) and **21** sufficed to confirm their nonidentity.

The generality of the cycloaddition of dichloroketene prepared by the zinc dechlorination procedure to cycloolefins was clearly demonstrated by the conversion of the representative examples shown in Table I to the corresponding cyclobutanones. In each reaction, the reductive dechlorination of the ketene–alkene cycloadduct afforded a *single* cyclobutanone. A structure proof of the cyclobutanones obtained from these reactions rested upon evidence from ^{13}C NMR (Table II) and on conversion of these cyclobutanones to the corresponding lactones and subsequent structure analysis in the latter series by ^1H and ^{13}C NMR studies (Table III). Of the lactones which appear in Table I, the synthesis of compounds **11** and **12** has been described previously by different routes. The identity of **11**[13] with the lactone obtained from 1-methylcyclopentene in this current study was indicated by a comparison of the ^1H NMR spectral properties of the compounds which contain a characteristic 1-H triplet at δ 4.43 and a methyl singlet at δ 1.27. Similarly, the occurrence of a 1-H multiplet at δ 4.50 in the 100-MHz spectrum of **12** agreed with that previously reported for this compound.[14]

The appearance of a ^1H triplet in the ^1H NMR spectra of the lactones **7–9** and **11** is attributable to the signal from an angular methine hydrogen bearing an acyloxy function. Not only does this imply that the lactones have the

Table I

alkene	cyclobutanones	lactones
		 7
		 8
		 9
	 10	 11
	 13	 12
	 14	 15
	 16	 17
	 18	 19

structures and stereochemistry shown but it also indicates that for lactones **7–9** the predominant conformation in solution is represented by the axial–aryl (alkyl) form **6a** rather than its conformer **6b** (vide infra).

The cyclobutanones **13** and **18** also have been described previously;[15] however, the 60–70% yields obtained for these compounds in this study were superior to those in the earlier reports.[16]

One important aspect of the results of the examples cited in Table I is that the cycloaddition process is both regio- and stereospecific in affording a single cyclobutanone adduct from each alkene. Over the course of examination of the reaction of dichloroketene with many additional examples of both cyclic and acyclic alkenes containing mono-, di-, and trisubstitution patterns, complete regio- and stereospecificity of the [2 + 2] cycloaddition reaction has been observed.[17]

(12) Tada, M.; Shinozaki, H.; Sato, T. *Tetrahedron Lett.* **1970**, 3897.
(13) Tsuda, Y.; Tanno, T.; Ukai, A.; Isobe, K. *Tetrahedron Lett.* **1971**, 2009.
(14) Brady, W. T. *Synthesis* **1971**, 415.
(15) (a) Ficini, J.; Maeyean, A. *C. R. Hebd. Seances Acad. Sci.* **1966**, *263*, 425. (b) Boldt, P.; Theelecke, W.; Etzenmuller, J. *Chem. Ber.* **1969**, *102*, 4157.
(16) (a) Brady, W. T.; Waters, O. H. *J. Org. Chem.* **1967**, *32*, 3703. (b) Turner, R. W.; Sedan, T. *Chem. Commun.* **1966**, 399. (c) Potts, T. R.; Harmon, R. E. *J. Org. Chem.* **1969**, *34*, 2792.
(17) In an improved procedure recently described,[10] Krepski and Hassner indicate that the dichlorocyclobutanones obtained from dichloroketene cycloaddition to 1-methylcyclohexene and indene are obtained in 79% and 81% yields, respectively. Since the reductive dechlorination of these compounds was not reported by these authors, a direct comparison of the yields is not possible; however, they would appear to be at least comparable to those reported in this study.

Table II. ^{13}C NMR Data of *cis*-Bicyclo[4.2.0]octanones

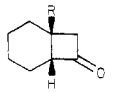
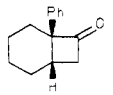
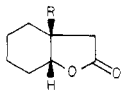
compd	chemical shift, δ								
	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	1-substituent
									
R = H	34.3	27.2	19.9	21.3	22.8	52.3	205.8	56.8	
R = Me	28.4	36.0	20.5	21.1	22.5	62.3	208.7	58.7	26.8 (CH_3)
R = $CH(CH_3)_2$	38.1	35.3	21.9	22.4	22.3	60.8	206.4	57.12	19.3 (CH_3), 18.1 (CH_3)
R = Ph	36.3	38.9	20.5	21.4	22.4	60.9	206.6	59.8	148.6 (1′-C), 126.1 (2′,6′-C), 128.3 (3′,5′-C), 126.2 (4′-C)
	67.0	32.8	20.4	25.1	29.1	37.0	47.1	209.2	142.7 (1′-C), 127.1 (2′,6′-C), 128.3 (3′,5′-C), 127.5 (4′-C)

Table III. ^{13}C NMR Data of Lactones

	chemical shift, δ								
	C-2	C-3[a]	C-3a[a]	C-4	C-5	C-6	C-7	C-7a[a]	3a-substituent
R = H	176.8	37.4	34.8	27.8	20.0	22.9	27.2	78.7	
R = Me	176.6	45.1	38.1	33.1	20.9	21.8	25.5	84.0	19.9 (CH_3)
R = $CH(CH_3)_2$	176.9	38.8	44.6	29.3	19.5	26.0	28.9	81.4	18.7 $CH(CH_3)_2$, 17.7 (CH_3)
R = Ph	175.5	46.8	45.8	34.4	19.6	20.9	26.3	81.7	142.4 (1-C), 126.4 (2′,6′-C), 128.8 (3′,5′-C), 127.0 (4′-C)

[a] Assignments supported by off-resonance studies.

The transformations of the cycloalkenes containing a disubstituted double bond represented in Table I do not present any structural ambiguities in the derived cyclobutanones with the possible exception of 1,2-dihydronapthalene. The structures of the cycloadducts derived from indene and cyclohexene with dichloroketene have been described previously,[18] and each was converted to the corresponding lactones **12** and **19** by Baeyer–Villiger oxidation of the intermediate cyclobutanones **13** and **18**, respectively.

The NMR spectral properties of the above cyclobutanones and the corresponding lactones provided useful correlative data (see Tables II and III) in supporting the structures of **16** and **17** of the cyclobutanone and lactone products derived from 1,2-dihydronapthalene (see Experimental Section and the tables).

Conformational Studies

The lactones **12** and **7–9** derived from cyclohexene and 1-substituted cyclohexenes may exist in the cyclohexane chair conformations **6a** and **6b**. A clear indication that the predominant conformation in *all* members of this series corresponds to the conformation **6a** (Chart I) was readily evident from ^1H NMR spectra of these compounds obtained at 250 MHz. The H-7a signal appeared as a symmetrical triplet (J_{app} = 3.0–4.0 Hz) in each of the lactones **7–9** and as quartet in the unsubstituted lactone **12**. In the former series the H-7a signal may be considered as the X part of an ABX subset, and as such the splitting pattern observed is only consistent with the existence of these compounds as a single *major* conformational type represented by **6a** in which the 7a-proton is equatorial and approximately equally coupled to the neighboring 7ax- and 7eq-protons.

The preference for conformation **6a** was also established for the unsubstituted lactone **12**. Double-resonance studies demonstrated that the appearance of the H-7a signal as a quartet was a consequence of each of the three couplings $J_{7a,7ax}$, $J_{7a,7eq}$, $J_{7a,3a}$ having approximately the same value of 4.0 Hz, a result which is only compatible with the equatorial disposition of H-7a in consonance with conformer **6a**.

While the preponderance of conformer **6a** over **6b** is expected for *cis*-octahydrobenzo[*b*]furan-2-one (**12**), the energy difference favoring **6a** is much larger than the 1.0 kcal estimated since introduction of various groups at the 3a-position such as phenyl, isopropyl, etc. apparently fails to disturb the equilibrium significantly in the direction of **6b**. The origin of the apparently large energy difference between **6a** and **6b** is not clear. In relation to this question it should be pointed out that mesembrine and related 1-aryl-*cis*-octahydroindoles adopt the analogous conformation in which the aryl group is axial.[3]

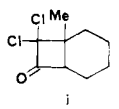
Experimental Section

Melting points were taken on a Thomas-Hoover capillary apparatus and are uncorrected. Infrared spectra were recorded on Perkin-Elmer 497 and 621 spectrophotometers. NMR spectra were run on a JEOL MH-100, a JEOL FX-60, a JEOL-FX90, and a Bruker WM-250 using tetramethylsilane as an internal standard. All chemical shifts are reported in δ units relative to Me_4Si in $CDCl_3$ solution unless otherwise stated.

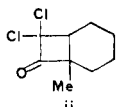
Gas chromatography was carried out by using F&M Model 402 and Varian 1200 gas chromatographs equipped with flame-ionization detectors. The standard columns used included glass and metal columns (8 ft × 0.25 in.) packed with 4% OV-17 on Varaport B, 4% SE-30 on Aeropak 30, and 4% Carbowax 20M on Aeroport 30. Mass spectra were recorded on MS-902 and Du Pont 491 mass spectrometers.

Elemental analyses were performed by M-H-W Laboratories, Garden City, MI, and by Galbraith Laboratories, Knoxville, TN.

(18) This finding accords with studies in other laboratories,[18] the only exception being the recent claim[11] that 1-methylcyclohexene gives a 4:1 mixture of the regioisomeric cyclobutanones i and ii based upon GC analysis of the reaction mixture after reductive dechlorination. Unfortunately the authors did not report the isolation or provide any spectral data to support the characterization of the minor isomer ii.



i



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Carbon-13 spectral details which appear in Tables II and III are not repeated in this section.

General Methods. (a) Ketene Cycloadditions. A well-stirred suspension of the alkene (10–40 mmol) and freshly prepared activated zinc (2.5 mmol/mmol of alkene) in dry ether (100–200 mL) was brought to reflux. Trichloroacetyl bromide 3mmol/mmol of alkene) in ether (40–100 mL) was added dropwise to the stirred suspension over a 4–6-h period while additional quantities of activated zinc (9.5 mmol/mmol of alkene) was added portionwise over the same time period. Refluxing was continued for an additional 2–4 h. The ethereal reaction mixture was filtered through Celite and the filtrate transferred to a separating funnel where it was washed with several aliquots of water. After drying the ethereal solution over $MgSO_4$, the solvent was removed in vacuo, and the crude dichlorocyclobutanone was subjected immediately to reductive dechlorination by one of the two procedures described below. Where deviations from this procedure occurred, they are noted.

(b) Reductive Dechlorination. Method 1. To a solution of the dichlorocyclobutanone in glacial acetic acid, zinc dust was added in one portion and the mixture was then refluxed from 4–24 h. After cooling the solution it was diluted with water and extracted three times with chloroform. The chloroform was then washed with water until the washings were neutral and then dried over Na_2SO_4 or $MgSO_4$. Evaporation of the solvent afforded the crude cyclobutanone containing reduced dichloroketene polymer. Purification was effected by chromatography and/or vacuum distillation.

Method 2. The dichlorocyclobutanone was dissolved in methanol, and to this was added in one portion a mixture of zinc dust and ammonium chloride. After the initial exothermic reaction had subsided, the reaction mixture was refluxed for 10–18 h. After the solution was filtered, the methanol was flash evaporated, leaving a semisolid residue. This was dissolved in water and extracted with methylene chloride. The organic layer was then dried over $MgSO_4$, filtered, and flash evaporated, leaving the crude cyclobutanone-containing polymeric material.

1-Phenyl-*cis*-bicyclo[4.2.0]octan-7-one (4, R = Ph). 1-Phenyl-1-cyclohexene (3.75 g) was reacted with activated zinc and Cl_3CCOBr in the described manner. After the workup, 4.4 g of brown oil (89% one component by GC on SE-30 at 250 °C) was obtained: IR (neat) ν_{max} 1805 cm^{-1} (α,α-dichlorocyclobutanone); NMR δ 7.2–7.4 (m, 5 H, aromatic), 4.2–4.0 (m, 1 H, angular H), 2.4–1.0 (m, 10 H, cyclohexyl). Reduction of the crude dichloro ketone (89% pure, 4.4 g) with zinc dust in HOAc afforded 3.4 g of an oil. Chromatography (180 g of grade I alumina) in 50% petroleum ether (bp 30–60 °C)–benzene afforded 2.9 g of pure ketone 4 (R = Ph). An analytical sample was obtained by distillation: bp 148–149 °C (5.1 mmHg); mp 39–40 °C; IR (neat) ν_{max} 1765 cm^{-1} (cyclobutanone); NMR δ (60 MHz) 7.3 (m, 5 H, aromatic), 3.6–3.4 (m, 1 H angular H), 3.2–3.16 (m, 2 H, cyclobutyl CH_2), 2.7–1.0 (m, 8 H, cyclohexyl); mass spectrum, m/e (relative intensity) 200 (M^+), 158 (100), 143 (39), 130 (44), 129 (53), 115 (36), 91 (38). Anal. Calcd for $C_{14}H_{16}O$: M^+, m/e 200.1201; C, 83.96; H, 8.05. Found: M^+, m/e 200.1197; C, 84.09; H, 8.15.

3a-Phenyl-*cis*-octahydrobenzo[*b*]furan-2-one (7, R = Ph). To an ice-cold mixture of 51.4 mg (0.257 mmol) of ketone 4 (R = Ph), 0.11 mL (0.8 mmol) of trifluoroacetic anhydride, 44 mg (0.3 mmol) of disodium hydrogen phosphate, and 2 mL of methylene chloride was added 21 μL of 90% H_2O_2 (0.85 mmol), and the mixture was stirred at 0 °C for 15 min and then at room temperature for 21 h.

The mixture was extracted with saturated $NaHCO_3$, and the organic layer was dried ($CaCl_2$) and evaporated to afford 51.4 mg (93%) of 7 as a yellow oil, pure by GC on SE-30 at 180 °C. A sample was crystallized from cyclohexane–hexane to give needles: mp 50–51 °C; IR ν_{max} 1767 cm^{-1}; NMR δ (250 MHz) 7.24–7.40 (m, 5 H, aromatic) 4.91 (t, 1 H, $J_{7a,7ax} = J_{7a,7eq}$ = 3.3 Hz, H-7a) 2.71 (s, 2 H, H-3α and H-3β), 2.34–0.94 (m, 8 H, cyclohexyl); mass spectrum, m/e (relative intensity) 216 (67), 198 (49), 145 (39), 144 (100), 118 (53). Anal. Calcd for $C_{14}H_{16}O_2$: M^+, m/e 216.1150; C, 77.75; H, 7.46. Found: M^+, m/e 216.1159; C, 77.77; H, 7.51.

7a-Phenyloctahydrobenzo[*b*]furan-2-one (21). To an ice-cold mixture of 51.1 mg (0.255 mmol) of ketone **20**,[12] 0.11 mL (0.8 mmol) of trifluoroacetic anhydride, 44 mg (0.3 mmol) of disodium hydrogen phosphate, and 2 mL of methylene chloride was added 21 μL of 90% H_2O_2 (0.85 mmol), and the mixture was stirred at 0 °C for 15 min and then at room temperature for 21 h. The mixture was extracted with saturated $NaHCO_3$, and the organic layer was dried ($CaCl_2$), and evaporated to afford 45.4 mg (82%) of **21** as a yellow oil, pure by GC on SE-30 at 200 °C: IR (neat) ν_{max} 1774 cm^{-1}; NMR (60 MHz) δ 7.4 (m, 5 H, aromatic) 2.94–0.96 (m, 11 H, cyclohexyl and 2-CH_2); mass spectrum, m/e (relative intensity) 216 (100), 173 (100), 105 (100); mass spectrum calcd for $C_{14}H_{16}O_2$, m/e 216.1150 (M^+), found m/e 216.1152 (M^+).

1-Methyl-*cis*-bicyclo[4.2.0]octan-7-one (4, R = Me). Methyl-1-cyclohexene (3.84 g, 40 mmol) in 250 mL of sodium-dried ether was reacted with trichloroacetyl bromide (18 g, 76 mmol) and zinc to afford 4.4 g of a dark brown oil (95% one component by GC on SE-30 at 165 °C): IR (neat) ν_{max} 1801 cm^{-1} (cyclobutanone); NMR δ 3.68–3.44 (m, angular H), 2.4–0.93 (m, 13 H, cyclohexyl with CH_3 at 1.5); ^{13}C NMR 19.56, 19.95, 21.25, 22.10, 33.79, 43.79, 57.86, 63.74, 195.76 ppm.

The dichloro ketone (4.4 g) was reduced with zinc dust in methanol containing ammonium chloride to afford 3.9 g of a brown oil. Chromatography of the oil on 12 g grade I alumina in 50% petroleum ether (bp 30–60 °C)–benzene gave 1-methyl-*cis*-bicyclo[4.2.0]octan-7-one (3.24 g). An analytical sample was obtained by distillation: bp 79 °C (27 mmHg); IR ν_{max} 1779 cm^{-1} (cyclobutanone); NMR (60 MHz) δ 3.05–2.82, (m, 1 H, angular H), 2.82–2.38 (m, 2 H, cyclobutyl CH_2), 2.2–2.83 (m, 11 H, cyclohexyl with CH_3 at 1.4); mass spectrum, m/e (relative intensity) 96 (76) 85 (38), 81 (100), 78 (35), 77 (48). Anal. Calcd for $C_9H_{14}O$: M^+, m/e 138.1045; C, 78.21; H, 10.21. Found: M^+, m/e 138.1049; C, 77.97; H, 10.37.

3a-Methyl-*cis*-octahydrobenzo[*b*]furan-2-one (7, R = Me). To an ice cold mixture of 50.6 mg (0.37 mmol) of ketone 4 (R = Me), 0.11 mL (0.8 mmol) of trifluoroacetic anhydride, 44 mg (0.3 mmol) of disodium hydrogen phosphate, and 2 mL of methylene chloride was added 21 μL of 90% H_2O_2 (0.85 mmol), and the mixture was stirred at 0 °C for 15 min and then at room temperature for 21 h.

The mixture was extracted with saturated $NaHCO_3$, and the organic layer was dried ($CaCl_2$) and evaporated to afford 51.2 mg (90%) of 7 as a yellow oil, pure by GC on SE-30 at 180 °C: IR ν_{max} 1774 cm^{-1}; NMR (250 MHz) δ 4.16 (t, 1 H, $J_{7a,7ax} = J_{7a,7eq}$ = 3.68 Hz, H-7a), 2.32 (s, 2 H, H-3α and H-3β), 1.16 (s, 3 H, CH_3); mass spectrum, m/e (relative intensity) 154 (M^+), 108 (19), 82 (100), 67 (23), 56 (19), 55 (19). A sample was distilled in vacuo at 67 °C (18 mmHg) for analysis. Anal. Calcd for $C_9H_{14}O_2$: M^+, m/e 154.0993; C, 70.10; H, 9.15. Found: M^+, m/e 154.0975; C, 70.14; H, 9.60.

***cis*-Octahydrobenzo[*b*]furan-2-one (12).** A mixture of 187 mg (1.5 mmol) of ketone **13**,[19] 10 mL of 30% H_2O_2, and 500 mg of NaOH was stirred at 0 °C for a few minutes and then at room temperature for 2 h. Neutralization (to pH 7), extraction with $CHCl_3$, and drying afforded 180 mg of **15**. Cooling of the sample to 0 °C afforded 120 mg (60%) of pure material as a solid which melted at ~10 °C: IR ν_{max} 1767 cm^{-1}; NMR (250 MHz) δ 4.50 (q, 1 H, $J_{7a,7ax} = J_{7z,7eq} = J_{3\alpha,7}$ = 4.0 Hz, H-7a) 2.62 (4 lines, 1 H, $J_{3\alpha,3\beta}$ = 2.75 Hz, $J_{3\alpha,3\beta}$ = 16.54 H, H-3β); irradiation at δ 1.69 (H-7eq) or 1.62 (H-7ax) resulted in collapse of the quartet at δ 4.50 to a triplet; mass spectrum, m/e (relative intensity) 140 (M^+), 96 (39), 81 (61), 67 (61), 55 (45), 44 (100). An analytical sample was obtained by distillation at 70 °C (1.5 mmHg) in a Kugelrohr apparatus. Anal. Calcd for $C_8H_{12}O_2$: C, 68.55; H, 8.63; M^+, m/e 140.0837. Found: C, 68.54; H, 8.57; M^+, m/e 140.0839.

1-Methyl-*cis*-bicyclo[3.2.0]heptan-6-one (10). The cycloaddition, performed as described, with 1-methyl-1-cyclopentene (1.64 g) in 250 mL of ether gave 3.47 g (90%) of a dark oil containing the dichloro ketone: IR (neat) ν_{max} 1811 cm^{-1} (cyclobutanone); NMR (100 MHz) δ 3.66–3.48 (br m, 1 H, angular CH), 2.57–1.70 (m, 6 H cyclopentyl), 1.57 (s, 3 H, angular CH_3).

The dichloro ketone (3.47 g, 18 mmol) was dechlorinated with zinc in acetic acid to yield 1.23 g (55%) of a brown oil. Distillation of the oil afforded 960 mg [bp 74–75.5 °C (22 mmHg)] of pure ketone 10: IR ν_{max} 1769 cm^{-1} (cyclobutanone); NMR (100 MHz) δ 3.20–2.90 (br, 1 H, angular CH), 2.77 (s, 2 H, cyclobutyl CH_2), 2.24–1.57 (m, 6 H, cyclopentyl, 1.45 (s, 3 H, angular CH_3). The

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NMR spectrum was in good agreement with that reported.[20] Anal. Calcd for $C_8H_{12}O$: C, 77.42; H, 9.68. Found: C, 77.55; H, 9.84.

3a-Methyl-*cis*-hexahydrocyclpenta[*b*]furan-2-one (11). A mixture of 128 mg (1.03 mmol) of ketone **10**, 5 mL of 30% H_2O_2, and 500 mg of NaOH was stirred at 0 °C for 5 min and then at room temperature for 2 h. Neutralization to pH 7 with HCl, extraction with chloroform, and drying afforded 105 mg (78%) of lactone **11**: NMR (60 MHz) δ 4.43 (br 1 H, angular H, $W_{1/2}$ = 8 Hz), 2.4 (s, 2 H, CH_2–CO), 2.17–1.40 (complex m, 7 H, cyclopentyl), 1.27 (s, 3 H, angular CH_3). These spectral parameters agree well with the literature values reported for the compound.[13]

1-Isopropyl-*cis*-bicyclo[4.2.0]octan-7-one (4, R = CH(CH$_3$)$_2$). 1-Isopropylcyclohexene (5 g, 40 mmol) was treated with Cl_3CCOBr and activated zinc by the standard procedure to give the crude dichlorocyclobutanone (ν_{CO} 1795 cm^{-1}) and reduced directly with zinc and acetic acid to the afford an oil (6.49 g). Chromatography of the oil in hexane (800 mL), 10% benzene–hexane (500 mL), and benzene (2 L) over silica gel (100 g) afforded the ketone **6** (R = $CH(CH_3)_2$): 3.1 g; IR (neat) ν_{max} 1775 cm^{-1} (cyclobutanone); NMR (100 MHz) δ 2.98 (m, 1 H, H-6), 2.63 (AB q, 2 H, J = 15.0 Hz H-8) 1.02 (d, 3 H, J = 7.0 Hz, CH_3), 0.97 (d, 3 H, J = 7.0 Hz CH_3); an analytical sample was obtained by a Kugelrohr distillation, bp 84–86 °C (23 mmHg); mass spectrum calcd for $C_{11}H_{18}O$, m/e 166.1358 (M^+), found m/e 166.1352.

3a-Isopropyl-*cis*-octahydrobenzo[*b*]furan-2-one (9). The cyclobutanone **4** (R = $CH(CH_3)_2$; 332 mg, 2 mmol) was dissolved in CH_2Cl_2 (15 mL); K_2HPO_4 (522 mg, 3 mmol) was added followed by trifluoroacetic anhydride (630 mg, 6 mmol, 0.45 mL) and the mixture cooled to 0 °C. Hydrogen peroxide (98%, 204 mg, 6 mmol) was added over 10 min to a stirred solution of the reactants, and the usual workup gave an oil which crystallized from $CHCl_3$–hexane to give the furanone **9** as plates: 259 mg; mp 58–59 °C; NMR (250 MHz) δ 4.37 (t, 1 H, $J_{7a,7eq}$ = 3.8 Hz, H-7a) 2.36 (d, 1 H, $J_{3\alpha,3\beta}$ = 16.6 Hz, H-3α or H-3β); 2.00 (d, 1 H, $J_{3\alpha,3\beta}$ = 16.6 Hz, H-3α or H-3β), 0.85 (d, 3 H, J = 7.0 Hz, CH_3), 0.84 (d, 3 H, J = 7.0 Hz), CH_3). Anal. Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95. Found: C, 72.43; H, 9.86.

2a,3,8,8a-Tetrahydrocyclobuta[*b*]naphthalen-1(2*H*)-one (14). 1,4-Dihydronaphthalene (5.20 g, 40 mmol) was reacted with activated zinc and Cl_3CCOBr in the previously described manner. After the normal workup, 8.0 g of a dark brown oil was obtained: IR (neat) ν_{max} 1802 cm^{-1}; ^{13}C NMR, 27.41, 29.94, 46.16, 55.46, 87.82, 127.53, 128.38, 129.29, 134.54, 197.26 ppm. This material was then dehalogenated without further purification via method 1. The crude product obtained from this reaction was chromatographed on Al_2O_3 (activity 1, 400 g) in benzene–hexane and benzene–$CHCl_3$ mixtures. The pure ketone **14** (3.86 g) was then distilled at 70–76 °C (0.05 mm) in a Kugelrohr apparatus to give crystals: mp 66–68 °C; IR ν_{max} 1776.4 cm^{-1}; NMR (100 MHz) δ 7.32 (4 H, s), 3.74 (2 H, br s), 2.6–3.1 (6 H, br m). Anal. Calcd for $C_{12}H_{12}O$: C, 83.69; H, 7.02. Found: C, 83.85; H, 7.18.

3a,4,9,9a-Tetrahydronaphtho[2,3-*b*]furan-2(3*H*)-one (15). To an ice-cold mixture of the cyclobutanone **14** (161.4 mg, 0.938 mmol) trifluoroacetic anhydride (TFAA; 0.4 mL, 2.912 mmol), dipotassium hydrogen phosphate (160.16 mg, 1.092 mmol), and methylene chloride (10 mL) was added 76.44 μL (3.094 mmol) of 98% H_2O_2, and the mixture was stirred at 0 °C for 15 min and then at room temperature for 19 h. The mixture was then extracted with saturated $NaHCO_3$, and the organic layer was dried over $MgSO_4$, filtered, and flash evaporated, leaving an oil. The oil on vacuum distillation in a Kugelrohr oven at 110–112 °C (0.1 mmHg) gave 112.4 mg (63.8%) of the lactone **15**: IR ν_{max} 1776.4 cm^{-1}; NMR (100 MHz) δ 7.28 (4 H s), 5.2–5 (1 H, m), 3.0 (2 H, d), 2.8–2.6 (5 H, m). Anal. Calcd for $C_{12}H_{12}O_2$: C, 76.57; H, 6.43. Found: C, 76.72; H, 6.47.

2a,3,4,8b-Tetrahydrocyclobuta[*a*]naphthalen-2(1*H*)-one (16). 1,2-Dihydronaphthalene (2.6 g, 20 mmol) was reacted with activated Zn (10 g) and Cl_3CCOBr (9.0 mL) to give, after the usual workup, 4.8 g of the α,α-dichlorocyclobutanone as a dark brown oil: IR (neat) ν_{max} 1805 cm^{-1}; ^{13}C NMR 21.70, 27.28, 50.55, 54.90, 77.06, 88.55, 126.06, 128.06, 129.04, 131.37, 137.28, 198.30 ppm. This material was then dechlorinated via method 1 by dissolving it in 100 mL of glacial acetic acid and adding 12.5 g of zinc dust to the crude cyclobutanone **16** as an oil. Column chromatography of the oil with silica gel and elution with $CHCl_3$ yielded the pure ketone which was then distilled in a Kugelrohr apparatus at 78–81 °C (0.15 mmHg) to give the pure ketone in 71% overall yield: IR ν_{max} 1761.6 cm^{-1}; NMR (100 MHz) δ 7.12 (4 H, m), 3.62 (2 H, s), 2.8–2.6 (2 H, m), 2.2–2.0 (2 H, m). Anal. Calcd for $C_{12}H_{12}O$: C, 83.69; H, 7.02. Found: C, 83.75; H, 7.21.

3a,4,5,9b-Tetrahydronaphtho[2,1-*b*]furan-2(1*H*)-one (17). The cyclobutanone **16** (419.1 mg, 2.44 mmol), TFAA (1.044 mL), and K_2HPO_4 (482.02 mg) were dissolved in 8 mL of CH_2Cl_2, and the mixture was stirred at 0 °C for 15 min. At this point 199.5 μL of 98% H_2O_2 was added, and the solution was stirred a further 15 min at 0 °C and then 20 h at room temperature. After the usual workup, 247.3 mg (58.6%) of the lactone **17** was obtained. Further purification of the product was effected by column chromatography on grade I alumina to give the pure compound **17** as an oil upon elution with $CHCl_3$. An analytical sample was obtained by vacuum distillation at 112–115° (0.3 mmHg): IR ν_{max} 1773.0 cm^{-1}; NMR (100 MHz) δ 7.32 (4 H, s), 5.0 (1 H, m), 4.28 (1 H, d), 4.0 (1 H, m), 3.4–2.6 (5 H, m); mass spectrum calcd for $C_{12}H_{12}O_2$, m/e 188.0836 (M^+), found m/e 188.0837 (M^+).

3,3a,8,8a-Tetrahydro-2*H*-indeno[2,1-*b*]furan-2-one (19). To an ice-cold mixture of the ketone **18** (148.2 mg, 0.938 mmol), TFAA (0.4 mL, 2.912 mmol), and K_2HPO_4 (160.16 mg, 1.092 mmol) in 10 mL of CH_2Cl_2 was added 76.45 μL (3.094 mmol) of 98% H_2O_2. This was stirred 15 min at 0 °C and 24 h at room temperature. After the usual workup, 85.2 mg (64.3%) of an oil was obtained. An analytical sample of **19** distilled at 94–98 °C (0.05 mmHg): IR ν_{max} 1761 cm^{-1}; NMR δ (100 MHz) 7.32 (4 H, s), 5.28 (1 H, m), 4.0 (1 H, m), 3.28 (2 H, d). Anal. Calcd for $C_{12}H_{12}O_2$: C, 75.79; H, 5.79. Found: C, 75.77; H, 5.90.

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Registry No. 2 (R = Ph), 82732-35-2; **2** (R = Me), 52809-65-1; **2** (R = *i*-Pr), 82732-36-3; **4** (R = Ph), 39778-70-6; **4** (R = Me), 39778-69-3; **4** (R = *i*-Pr), 82732-29-4; **7**, 39778-74-0; **9**, 82732-31-8; **10**, 5212-68-0; **11**, 82732-30-7; **12**, 24871-12-3; **13**, 27655-70-5; **14**, 82732-32-9; **14** (dichloro derivative), 82732-37-4; **15**, 82732-33-0; **16**, 82732-34-1; **16** (dichloro derivative), 82732-38-5; **17**, 63319-92-6; **18**, 31996-70-0; **19**, 38506-17-1; **21**, 19946-69-1; 1-phenyl-1-cyclohexene, 771-98-2; 1-methyl-1-cyclopentene, 693-89-0; 1-isopropylcyclohexene, 4292-04-0; 1,4-dihydronaphthalene, 612-17-9; 1,2-dihydronaphthalene, 447-53-0; dichloroketene, 4591-28-0.

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