2. Preparation and *Diels-Alder* Reactivity of 2,3,5,6,7,8-Hexamethylidenebicyclo[2.2.2]octane ('[2.2.2]Hericene'). Force-Field Calculations of Exocyclic Dienes as a Moiety of Bicyclic Skeletons[1])[2])

by **Olivier Pilet**[3]), **Jean-Luc Birbaum** and **Pierre Vogel**[4])

Institut de chimie organique de l'Université, 2, rue de la Barre, CH-1005 Lausanne

(3.VIII.82)

Summary

The [2.2.2]hericene (**6**), a bicyclo[2.2.2]octane bearing three exocyclic *s-cis*-butadiene units has been prepared in eight steps from coumalic acid and maleic anhydride. The hexaene **6** adds successively three mol-equiv. of strong dienophiles such as ethylenetetracarbonitrile (TCE) and dimethyl acetylenedicarboxylate (DMAD) giving the corresponding monoadducts **17** and **20** (k_1), bis-adducts **18** and **21** (k_2) and tris-adducts **19** and **22** (k_3), respectively. The rate constant ratio k_1/k_2 is small as in the case of the cycloadditions of 2,3,5,6-tetramethylidene-bicyclo[2.2.2]octane (**3**) giving the corresponding monoadducts **23** and **27** (k_1) and bis-adducts **25** and **29** (k_2) with TCE and DMAD, respectively. Contrastingly, the rate constant ratio k_2/k_3 is relatively large as the rate constant ratio k_1/k_2 of the *Diels-Alder* additions for 5,6,7,8-tetramethylidenebicyclo[2.2.2]oct-2-ene (**4**) giving the corresponding monoadducts **24** and **28** (k_1) and bis-adducts **26** and **30** (k_2). The following second-order rate constants (toluene, 25°) and activation parameters were obtained for the TCE additions: **3** + TCE → **23**: $k_1 = 0.591 \pm 0.012$ mol$^{-1} \cdot$ l $\cdot$ s^{-1}, $\Delta H^{+} = 10.6 \pm 0.4$ kcal/mol, and $\Delta S^{+} = -24.0 \pm 1.4$ cal/mol $\cdot$ K (e.u.); **23** + TCE → **25**: $k_2 = 0.034 \pm 0.0010$ mol$^{-1} \cdot$ l $\cdot$ s^{-1}, $\Delta H^{+} = 10.6 \pm 0.6$ kcal/mol, and $\Delta S^{+} = -29.7 \pm 2.0$ e.u.; **4** + TCE → **24**: $k_1 = 0.172 \pm 0.035$ mol$^{-1} \cdot$ l $\cdot$ s^{-1}, $\Delta H^{+} = 11.3 \pm 0.8$ kcal/mol, and $\Delta S^{+} = -24.0 \pm 2.8$ e.u.; **24** + TCE → **26**: $k_2 = (6.1 \pm 0.2) \cdot 10^{-4}$ mol$^{-1} \cdot$ l $\cdot$ s^{-1}, $\Delta H^{+} = 13.0 \pm 0.3$ kcal/mol, and $\Delta S^{+} = -29.5 \pm 0.8$ e.u.; **6** + TCE → **17**: $k_1 = 0.136 \pm 0.002$ mol$^{-1} \cdot$ l $\cdot$ s^{-1}, $\Delta H^{+} = 11.3 \pm 0.2$ kcal/mol, and $\Delta S^{+} = -24.5 \pm 0.8$ e.u.; **17** + TCE → **18**: $k_2 = 0.0156 \pm 0.0003$ mol$^{-1} \cdot$ l $\cdot$ s^{-1}, $\Delta H^{+} = 10.9 \pm 0.5$ kcal/mol,

[1]) Interaction between non-conjugated chromophores, Part 18. Part 17, see [1]. For a preliminary report see [2a]. An exocyclic diene means that each double bond is in an exocyclic position on the ring skeleton.

[2]) The shortening '[l.m.n]hericene' is used for bicyclo[l.m.n]alkanes with l + m + n methylidene groups, after the latin name *hericeus* for hedgehog. We thank Prof. *H. Wyler* for suggesting us this resemblance. For the 7,7-dimethyl[2.2.1]hericene, see [2b].

[3]) Present address: Stanford University, Dept. of Chemistry, Stanford, Calif. 94305.

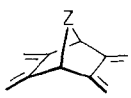
[4]) Author to whom correspondence should be addressed.

and $\Delta S^{\neq} = -30.1 \pm 1.5$ e.u.; **18** + TCE → **19**: $k_3 = (5 \pm 0.2) \cdot 10^{-5}$ $mol^{-1} \cdot l \cdot s^{-1}$, $\Delta H^{\neq} = 15 \pm 3$ kcal/mol, and $\Delta S^{\neq} = -28 \pm 8$ e.u. The following rate constants were evaluated for the DMAD additions (CD_2Cl_2, 30°): **6** + DMAD → **20**: $k_1 = (10 \pm 1) \cdot 10^{-4}$ $mol^{-1} \cdot l \cdot s^{-1}$; **20** + DMAD → **21**: $k_2 = (6.5 \pm 0.1) \cdot 10^{-4}$ $mol^{-1} \cdot l \cdot s^{-1}$; **21** + DMAD → **22**: $k_3 = (1.0 \pm 0.1) \cdot 10^{-4}$ $mol^{-1} \cdot l \cdot s^{-1}$.

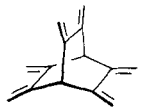
The reactions giving the barrelene derivatives **19**, **22**, **26** and **30** are slower than those leading to adducts that are not barrelenes. The former are estimated less exothermic than the latter. It is proposed that the *Diels-Alder* reactivity of exocyclic *s-cis*-butadienes grafted onto bicyclo[2.2.1]heptanes and bicyclo[2.2.2]octanes that are modified by remote substitution of the bicyclic skeletons can be affected by changes in the exothermicity of the cycloadditions, in agreement with the *Dimroth* and *Bell-Evans-Polanyi* principle.

Force-field calculations (MMPI 1) of **3**, **4**, **6** and related exocyclic *s-cis*-butadienes as a moiety of bicyclo[2.2.2]octane suggested single minimum energy hypersurfaces for these systems (eclipsed conformations, planar dienes). Their flexibility decreases with the degree of unsaturation of the bicyclic skeleton. The effect of an endocyclic double bond is larger than that of an exocyclic diene moiety.

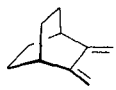
Introduction. – The spectroscopic [3] and chemical properties of an exocyclic *s-cis*-butadiene moiety of a bicyclic skeleton can be modified by remote substitution [4–10]. The 2,3,5,6-tetramethylidenebicyclo[2.2.n]alkanes are very attractive starting materials for the preparation of polycyclic, polyfunctional systems by two



1 Z = O
2 Z = CH_2
3 Z = CH_2–CH_2
4 Z = CH=CH
5 Z = CH–CH (O)



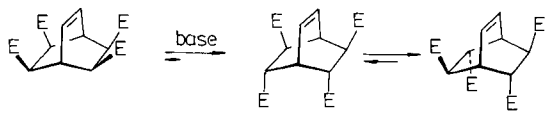
6



7

successive *Diels-Alder* additions with different dienophiles. The 2,3,5,6-tetramethylidene-7-oxabicyclo[2.2.1]heptane (**1**) [11] can be used to prepare various anthracycline derivatives [12]. The principle of our strategy rests upon the fact that the rate of the *Diels-Alder* addition of **1** (k_1) is much higher than that (k_2) of the corresponding monoadduct. A relatively high rate constant ratio k_1/k_2 was also measured for the ethylenetetracarbonitrile (TCE) additions to 2,3,5,6-tetramethylidenebicyclo[2.2.1]heptane (**2**) [10] and to 7-isopropylidene-2,3,5,6-tetramethylidenebicyclo[2.2.1]heptane [2b]. We now report an efficient synthesis of the [2.2.2]hericene[2] (**6**). We shall compare its *Diels-Alder* reactivity with that of its monoadducts and bis-adducts and also with that of the tetramethylidene compounds **3** and **4** [13]. We shall show that the rate constant ratio k_1/k_2 varies with the nature of the bridge *Z* in **1**–**6**.

Synthesis of [2.2.2]hericene. – Double carbomethoxylation of maleic anhydride adduct with cyclopentadiene [10] or furan [11b] yielded the corresponding tetramethyl bicyclo[2.2.1]heptane-2,3,5,6-tetracarboxylates in one step and in excellent

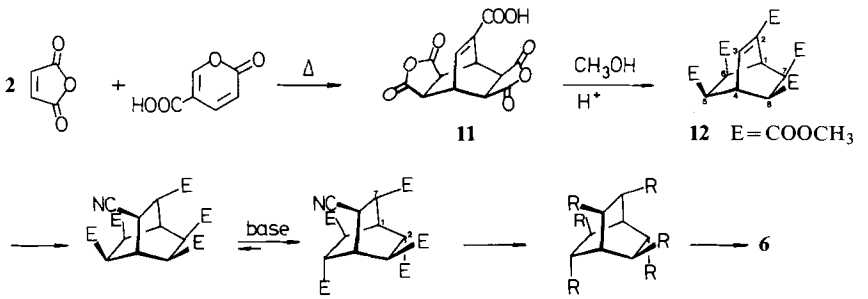


8 a E = $COOCH_3$, b E = $COOC_2H_5$ **9** **10**

yield. Although the double carbomethoxylation of bicyclo[2.2.2]oct-2-ene gave dimethyl bicyclo[2.2.2]octane-2,3-dicarboxylate in 80% yield (which was transformed to **7** in the usual manner, see below), no trace of the corresponding hexaesters could be obtained by treating the methyl or ethyl tetraesters **8–10** under the usual conditions of the Pd-catalyzed double carbomethoxylation reaction [2b] [10] [11b]. This can be attributed to the bulk of the ester groups that prohibits the Pd(II) coordination of the double bond in **8–10**. The tetraesters **10** were the major products formed (*ca.* 80%) by K_2CO_3-catalyzed isomerization of **8** [6]. The isomer **9a** was obtained under kinetic control (precipitation) by MeONa-catalyzed isomerization of **8a** in absolute MeOH. Double carbomethoxylation of the tetrakis-(hydroxymethyl)- and tetrakis(chloromethyl) derivatives of **8–10** failed also.

Pentamethyl bicyclo[2.2.2]oct-2-ene-2,5,6,7,8-pentacarboxylate (**12**) [14] was obtained by heating a 3:1 mixture of maleic anhydride and coumalic acid (2-oxo-2*H*-pyran-5-carboxylic acid) to 200° without solvent, yielding the bis-anhydride **11**, followed by esterification (87%). The 'all-*cis*'-configuration of the ester groups one to each other in **12** was indicated by the $^3J(H,H) = 2.0$ Hz between H–C(6)/H–C(7) and H–C(1) and between H–C(5)/H–C(8) and H–C(4), and by $^3J(C,H) \approx 2$ Hz between C(3) and H–C(1)/H–C(5)/H–C(8) [15]. Confirmation of this structural assignment was given by comparison with the ^1H- and ^{13}C-NMR. data of the methyl tetraesters **8a** and **9a** [**8a**: $^3J(H–C(4), H_{endo}–C(5)/H_{endo}–C(8)) = 2.2$–$2.7$ Hz; **9a**: $^3J(H–C(4), H_{exo}–C(5)/H_{exo}–C(8)) < 2.0$ Hz [16]; $^3J(C(3),-H_{endo}–C(5)/H_{endo}–C(8))$ of **8a** $> {}^3J(C(3), H_{exo}–C(5)/H_{exo}–C(8))$ of **9a**].

When **12** was heated to 80° for 20 h with KCN, $(CH_3)_2C(OH)CN$ and a small amount (0.05 mol-equiv.) of tetrabutylammonium cyanide in anhydrous CH_3CN, the cyano-pentaester **13** was obtained (> 97%). This technique of 1,4-cyanation was found to be more practical and gave better yields than *Liotta*'s method using



11 **12** E = $COOCH_3$

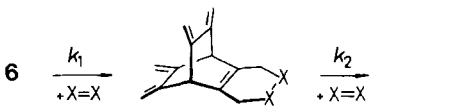
13' **13**

14 R = $COOCH_3$
15 R = CH_2OH
16 R = CH_2Cl

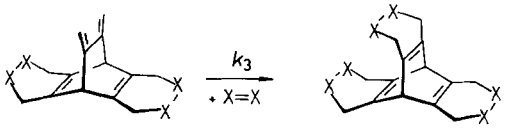
18-crown-6 ether [17]. Under these conditions, base-catalyzed isomerization of the pentaester was complete and gave the 'all-*trans*'-isomer **13** as major product. Hydrolysis ($AcOH/H_2O/H_2SO_4$) of **13** followed by esterification with MeOH ($CHCl_3$/TosOH) gave the 'all-*trans*'-hexaester **14** in good yield (85%). Reduction with $LiAlH_4$ in THF yielded the hexol **15** (41%) which was transformed into the hexachloride **16** upon treatment with $SOCl_2$ in pyridine (45%). Elimination of 6 equiv. of HCl was achieved by heating **16** with an excess of *t*-BuOK in THF (3 days) or in DMF/hexamethylphosphoric triamide (HMPTA) 3:1 (3 h) to 50°, yielding the [2.2.2]hericene (**6**), a nice crystalline, colourless compound (global yield: 7% from **12**). A better global yield was obtained for **6** (29% from **12**) when the 1,4-cyanation of **12** was carried out in 4 h in CH_3CN/H_2O 99:1 instead of 20 h in CH_3CN, giving a mixture of partially isomerized pentaesters (**13'**+isomers). The corresponding partially isomerized hexols **15'** and hexachlorides **16'** (whose configuration has not been assigned) were obtained in better yield, probably because of their better solubilities (see *Exper. Part*). The structures of compounds **13**–**16** and **6** were deduced from their spectral data, from their mode of formation and from their combustion analyses.

The UV. absorption spectrum of **6** compared with those of the tetramethylidene compounds **3** and **4** and the dimethylidene derivative **7** [2a] [18], as well as the PE. spectra of these olefins [3b] gave evidence of a transannular interaction between the exocyclic *s-cis*-butadiene units of **3**, **4** and **6**.

Strong dienophiles such as TCE and dimethyl acetylenedicarboxylate (DMAD) added to **6** giving the corresponding monoadducts **17** and **20**, bis-adducts **18** and **21** and tris-adducts **19** and **22**, respectively.

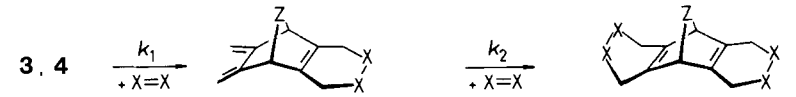


X=X: TCE **17** X–X=$(NC)_2C$–$C(CN)_2$
DMAD **20** X–X=CH_3OOCC=$CCOOCH_3$



18 X–X=$(NC)_2C$–$C(CN)_2$ **19** X–X=$(NC)_2C$–$C(CN)_2$
21 X–X=CH_3OOCC=$CCOOCH_3$ **22** X–X=CH_3OOCC=$CCOOCH_3$

***Diels-Alder* reactivity of [2.2.2]hericene and related tetramethylidene- and dimethylidenebicycloalkanes.** – The second-order rate constants of the TCE cycloadditions to **6** (k_1), **17** (k_2) and **18** (k_3) measured in toluene at various temperatures allowed the evaluation of the activation parameters reported in *Table 1* together with those obtained for the TCE additions to the tetramethylidene compounds **3** and **4** (k_1) and their corresponding monoadducts **23** and **24** (k_2).



23 Z = CH_2–CH_2; X–X = $(NC)_2C$–$C(CN)_2$
25 Z = CH_2–CH_2; X–X = $(NC)_2C$–$C(CN)_2$
27 Z = CH_2–CH_2; X–X = CH_3OOCC=$CCOOCH_3$
29 Z = CH_2–CH_2; X–X = CH_3OOCC=$CCOOCH_3$

24 Z = CH=CH; X–X = $(NC)_2C$–$C(CN)_2$
26 Z = CH=CH; X–X = $(NC)_2C$–$C(CN)_2$
28 Z = CH=CH; X–X = CH_3OOCC=$CCOOCH_3$
30 Z = CH=CH; X–X = CH_3OOCC=$CCOOCH_3$

The rate constant k_3 for the formation of the tris-adduct **19** was much smaller than those of the TCE additions to **6** (k_1) and **17** (k_2). It was measured under conditions of second-order rate law for the disappearance of the TCE-toluene complex (λ_{max} = 405 nm). The low solubility of **18** did not permit to work under pseudo-first-order rate law conditions, and it is responsible for the relatively large errors given for the activation parameters of this reaction. The rate constants k_1 and k_2 for the TCE additions to **6** and **17**, respectively, were obtained under pseudo-first-order rate law conditions using 15- to 1000fold excesses of **6** and **17** and by measuring the disappearance of the TCE-toluene complex for 3–4 half-lives. In the case of **17** + TCE → **18** (k_2), the contribution of the reaction **18** + TCE → **19** (k_3) did not perturb the direct evaluation of k_2 as the rate constant ratio k_2/k_3 was 250–400. In the case of **6** + TCE → **17** (k_1), appropriate (minor) corrections were made (computer) for the known contribution of k_2. The rate constants k_1 and k_2 were also measured under second-order rate law conditions using the *GENLSQ* programme [19] to compare experimental and simulated (computer) kinetics. Within experimental error limits, the two techniques gave the same values (at a given temperature) for the second-order rate constants. There was no observable effect on k_1, k_2 and k_3 due to changes of the initial concentrations of the cycloaddents ([TCE] = $(1.5-5.2) \cdot 10^{-4}$ mol/l; ['diene'] = 10^{-4} to 0.58 mol/l) or due to changes in their initial concentration ratios. The second-order rate constants for the TCE cycloadditions to **3** and **4** (k_1) and their monoadducts **23** and **24** (k_2) were obtained using the same techniques *(Table 1)*.

The rate constants of the *Diels-Alder* additions of DMAD to **6**, **20** and **21** were measured under pseudo-first-order rate law conditions (20–30fold excess of DMAD, measuring the disappearance of the vinylic proton signals by ^{1}H-NMR.). They are reported in *Table 2* together with the values obtained for k_1 and k_2 of the DMAD addition to **3** and **4** and their monoadducts **27** and **28**, respectively.

The relatively large rate constant ratio k_2/k_3 = 320 measured at 25° for the TCE additions to **17** *vs.* **18** contrasts with the small rate constant ratio k_1/k_2 = 8 for the TCE additions to **6** *vs.* **17**. Interestingly, a rate constant ratio k_1/k_2 = 282 was measured for the TCE additions to **4** *vs.* **24** (the pentaene **4** can be considered as a model compound of the monoadduct **17**), whereas a rate constant ratio k_1/k_2 = 17 was evaluated for the TCE additions to **3** *vs.* **23**. Noteworthy is also the similarity in the reactivities of **3**, **4**, **6**, **7** and 5,6-dimethylidenebicyclo[2.2.2]oct-2-ene (**31**; see *Table 1*). The relatively large reactivity decrease observed when comparing **18** + TCE with **17** + TCE and **24** + TCE with **4** + TCE are somewhat surprising con-

Table 1. *Kinetic data of the cycloadditions of TCE to* **6**, **17**, **18**, **3**, **23**, **4**, **24**, **7** *and 5,6-dimethylidenebicyclo[2.2.2]oct-2-ene* (**31**) *in toluene, and experimental* IP's

'Diene'	$k^{II} \cdot 10^4$ [$mol^{-1} \cdot l \cdot s^{-1}$][a]) (Temperature of the measurements ±0.05 K)					$\Delta H^{\neq}$ [kcal/mol] (T_m)	$\Delta S^{\neq}$ [e.u.] (ΔT)	$k^{II} \cdot 10^4$ (298 K)[b]) [$mol^{-1} \cdot l \cdot s^{-1}$]	*IP* [eV]
6	435	878	1870	3460	5710	11.3±0.2	−24.5±0.8	1360	8.38
	(282.1 K)	(291.8 K)	(302.7 K)	(312.4 K)	(321.2 K)	(302 K)	(39.1 K)	±20	[3b]
17	109	213	363	633	1120	10.9±0.5	−30.1±1.5	156	
	(293.0 K)	(302.5 K)	(312.0 K)	(321.1 K)	(331.7 K)	(312 K)	(38.7 K)	±3	
18	6.1	30	57			15±3	−28±8	0.5	
	(331.8 K)	(355.0 K)	(366.0 K)			(351 K)	(34.2 K)	±0.02	
3	2490	4310	8090	13700	22800	10.6±0.4	−24.0±1.4	5910	8.36
	(285.1 K)	(293.4 K)	(302.6 K)	(312.1 K)	(311.1 K)	(303 K)	(36 K)	±120	[3a]
23	115	225	460	750	1400	10.6±0.6	−29.7±2.0	334	
	(282.2 K)	(292.1 K)	(302.6 K)	(312.1 K)	(322.2 K)	(302 K)	(40 K)	±10	
4	715	1170	2310	4290	7400	11.3±0.8	−24.0±2.8	1720	8.37
	(285.1 K)	(293.4 K)	(306.6 K)	(312.1 K)	(321.3 K)	(303 K)	(36.2 K)	±35	[3a]
24	4.17	8.58	17.2	32.3	57.5	13.0±0.3	−29.5±0.8	6.1	
	(293.4 K)	(302.6 K)	(312.1 K)	(321.2 K)	(330.5 K)	(312 K)	(37.1 K)	±0.2	
7								19000	8.37
								[21]	[3f]
31								6700	8.33
								[21]	[3f]

[a]) Statistical standard deviations for 6–10 independent measurements with 3–5 different solutions of the polyolefins and TCE were found to be within 1–2%.
[b]) Inter- or extrapolated to 298 K.

Table 2. *Kinetic data of the cycloadditions of DMAD to* **6**, **20**, **21**, **3**, **27**, **4** *and* **28**

'Diene'	**6**	**20**	**21**	**3**	**27**	**4**	**28**
$k^{II} \cdot 10^4$ [mol^{-1} · l · s^{-1}]	10 ± 1	6.5 ± 0.1	1.0 ± 0.1	48[a])	48[a])	13.1[a])	1.2[a])
T [°C]	30	30	30	50	50	50	50
Solvent	CD_2Cl_2	CD_2Cl_2	CD_2Cl_2	CCl_4	CCl_4	CCl_4	CCl_4

[a]) See [13b].

sidering that we are dealing with remote substituent effects on the *Diels-Alder* reactivity of exocyclic *s-cis*-butadiene moieties of similar skeletons. These reactivity differences must be compared with the *Diels-Alder* additions involving systems that have different substituents directly attached to the diene function. For instance, the 2-methoxybutadiene reacts 'only' 40 times as fast as isoprene toward TCE [20].

The *Diels-Alder* reactivity of DMAD to **3**, **4** and **6** follows a trend similar to that of TCE but at strong attenuated rate ratios. For both **3** and **6** k_1/k_2 was *ca.* 1, whereas for **6** $k_2/k_3 = 6.5$ and for **4** $k_1/k_2 = 12$. Once corrected for the statistical factor of the number of mol-equiv. exocyclic diene moieties, these rate ratios are relatively small.

Discussion. – *A priori*, the *Diels-Alder* reactivity of our exocyclic dienes can be affected by several factors [22], *e.g.*: 1) by the geometry of the diene (1,4-distance between the exocyclic methylidene C-atoms [22b], conformation of the diene [22] [23]) and rigidity of the bicyclic skeleton, 2) by the polarizability of the diene [24] (ionization potentials (*IP*) [25]), and 3) by the exothermicity of the reactions. With strong dienophiles such as TCE, DMAD, methyl vinyl ketones, acrylates and benzoquinone, the compounds **1** and **2** with the four methylidene groups inserted into rigid bicyclo[2.2.1]heptane skeletons showed a relatively large reactivity difference for their *Diels-Alder* additions compared with those of their corresponding monoadducts ($k_1/k_2 = 350$–400 for TCE, toluene, 25°) [10]. One part of this effect could be attributed to a change in the *IP*'s when going from the tetramethylidene compound to the corresponding monoadduct, although the experimental *IP*'s measured for **1**, **2**, 5,6-dimethylidenebicyclo[2.2.1]hept-2-ene and 5,6-dimethylidene-7-oxabicyclo[2.2.1]hept-2-ene were not strongly convincing [3a]. The crystal X-ray structure of related exocyclic dienes suggested that the geometry of the butadiene unit (1,4-distance, conformation) does not change between a tetramethylidene compound and the corresponding monoadducts. The X-ray structure of **6** [18] suggested a planar conformation for the exocyclic diene moieties of the bicyclo[2.2.2]octane skeleton, although *van der Waals* repulsion between the 'internal' H-atoms of the butadiene moieties were thought to favour out-of-plane deformations (the hexamethylidene compound **6** was believed to be the best possible bicyclo[2.2.2]octane derivative where this effect should be visible since it bears 3 butadiene units).

The cycloadditions of **1** and **2** were evaluated to be more exothermic than those of their monoadducts because the latter generate trinorbornadienes and 7-oxatrinorbornadienes, respectively, systems that are more strained than the tetramethylidene compounds **1** and **2** and their monoadducts due to hyperconjugative

interactions. These $\sigma \leftrightarrow \pi$ repulsive phenomena are thought to be responsible for the out-of-plane deformations (π-anisotropy) of the endocyclic double bonds of these compounds [26]. It is usually assumed that a *Diels-Alder* addition has an early transition state and, therefore, should not be affected significantly by variation in the exothermicity. We think that the *Dimroth* [27] and *Bell-Evans-Polanyi* principle [28] cannot be ignored for the cycloadditions of our exocyclic dienes being modified by remote changes of the bicyclic skeleton. We have proposed that **1** and **2** could be more reactive than their monoadducts because their *Diels-Alder* additions are more exothermic than those of their monoadducts.

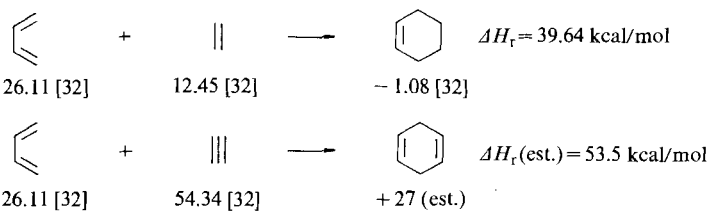
The insignificant changes observed in the *IP*'s of **3**–**7** and 5,6-dimethylidenebicyclo[2.2.2]oct-2-ene (**31**; *Table 1*) show that the reactivity trend of the TCE additions to these olefins and to the adducts **17**, **18**, **23** and **24** cannot be attributed to a variation of the polarizability of the exocyclic diene moiety as a function of the homoconjugated π-system (endocyclic double bond *vs.* exocyclic *s-cis*-butadiene unit). It is not excluded that the reactivity of a monoadduct is slightly reduced because of the inductive effect of the remote carbonitrile groups, although such an effect cannot be very important judging from the relatively small rate constant ratio k_1/k_2 observed for the TCE additions to **3** and **6**.

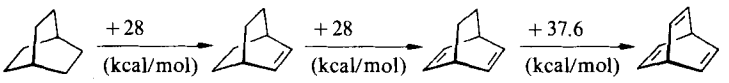
It is important to note that the rate constants and the activation enthalpies of the TCE additions to **6**, **17**, **3**, **23**, **4** are about the same *(Table 1)*. A net decrease of reactivity is observed only for the cycloadditions generating barrelene derivatives (**18** + TCE → **19**, **24** + TNE → **26**). Barrelene (bicyclo[2.2.2]octa-2,5,7-triene) [29] is known for its extra strain of *ca.* 10 kcal/mol [30] due to π-electron repulsions arising from the specific arrangements of its three endocyclic double bonds [31]. Thus, we predict that the exothermicity of the additions **18** + TCE → **19** and **24** + TCE → **26** are smaller than the one of the TCE cycloadditions to **3**, **6**, **17**, **23**, **7** and 5,6-dimethylidenebicyclo[2.2.2]oct-2-ene (**31**). If the difference in exothermicity is 6–10 kcal/mol it is not unreasonable to accept that it could lead to a change of *ca.* 2 kcal/mol in the $\Delta H^{\neq}$ term because of the *Dimroth* [27] and *Bell-Evans-Polanyi* principle [28]. The exothermicities of the reactions discussed here should be measured to put this hypothesis on firmer ground.

Although strongly attenuated, the reactivity trend of the *Diels-Alder* additions of DMAD to **6**, **3**, **4** and the corresponding adducts **20**, **21**, **27** and **28** follows the TCE reactivity trend. The cycloadditions of DMAD are estimated to be *ca.* 14 kcal/mol (without considering the loss of TCE resonance energy)[5]) more exothermic than those of TCE, thus making the transition states of the former reactions more

---

[5]) This value is obtained by comparison of the following hypothetical reactions:





cycloaddent-like than in the latter, and, consequently, less sensitive to a change of the exothermicity.

It is possible also that the variation of the rate constant ratio k_1/k_2 as a function of the nature of the bridge Z could be due to differences in the flexibility of the bicyclic skeleton; the more flexible the system, the faster it would react. We have evaluated this hypothesis by force-field calculations and we shall show that it cannot be retained.

Force-field calculations of exocyclic butadienes inserted into bicyclic skeletons. – We have applied *Allinger*'s MMPI 1 technique [33] to calculate the geometry of the dimethylidene compounds **7** and **31–33**, the tetramethylidene compounds **3** and **4**, and the hexamethylidene derivative **6**. All these compounds were found to prefer an eclipsed conformation with planar *s-cis*-butadiene moieties (single minimum energy hypersurfaces). The *van der Waals* repulsions between the methylidene groups are apparently insufficient to make the butadiene units deviate from planarity and the bicyclic skeletons to adopt staggered conformations. Since the *Diels-Alder* additions imply in the transition states some distortion in the diene

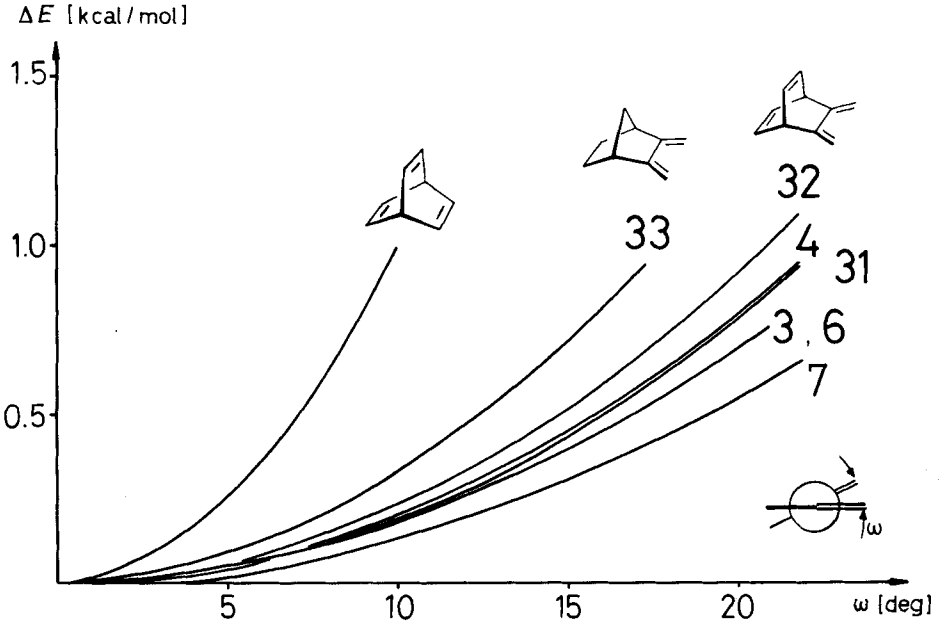


Fig. 1. *MMPI 1 Energy potentials of* **3**, **4**, **6**, **7** *and* **31–33** *as a function of the torsional angle* ω *of the exocyclic diene moiety* (all other geometrical factors being completely minimized). For comparison, the energy potential of barrelene as a function of the torsional angle about the C_3 axis is also shown.

geometry we had foreseen that the more flexible an exocyclic diene moiety, the faster it would react. In order to evaluate this flexibility we calculated the energy potentials of **3**, **4**, **6**, **7** and **31**–**33** as a function of the dihedral angle between two vicinal methylidene groups (torsional angle of the exocyclic diene ω). Our results are summarized in *Figure 1*. As already discussed by *Klessinger et al.* [34], we find the trinorbornane derivative **33** less flexible than the bicyclo[2.2.2]octane derivatives **7**, **31** and **32**. As expected intuitively, the introduction of sp^2-hybridized C-atoms into the bicyclo[2.2.2]octane skeleton decreases the flexibility of the exocyclic dienes. The effect is larger for an endocyclic double bond than for an exocyclic *s-cis*-butadiene moiety. Thus, we predict that the flexibility of the dienes decreases when going from **3**, **4** and **6** to their corresponding monoadducts. Very important in our context is the prediction that the decrease in flexibility is about the same when going from **6** to **4** (model compound of the monoadducts of **6**) and from **4** to **32** (model compound of the bis-adducts of **6** and monoadducts of **4**). If the flexibility of our exocyclic dienes should affect their *Diels-Alder* reactivity, and if our method to estimate it is reasonable and the force-field approach relevant, we thus predict that the rate constant ratios k_1/k_2 and k_2/k_3 should not depend upon the nature of the bridge Z in **1**–**6**.

According to the MMPI 1 calculations, the total *van der Waals* repulsions between the methylidene groups is not very large (see *Table 3*) for the planar buta-

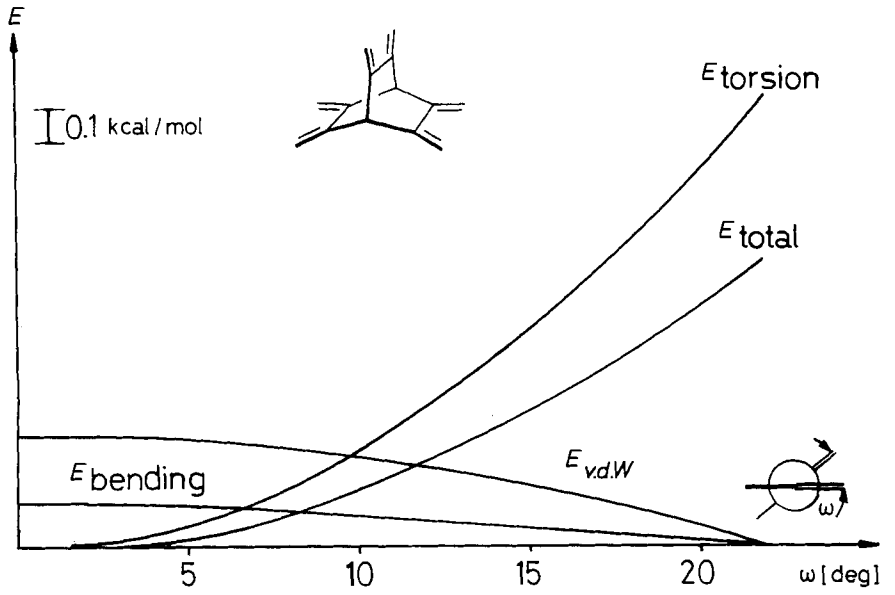


Fig. 2. *MMPI 1 Energy potential* (E_{tot}) *of* **6** *as a function of the torsional angle* ω *of the exocyclic diene moieties and variations of the calculated bending energies* ($E_{bending}$), van der Waals *repulsions* ($E_{v.d.W}$) *and torsional strain* ($E_{torsion}$). Similar curves were also calculated for **3**, **4**, **31** and **32**. To simplify, the represented energy scale is arbitrary; for $\omega = 0$ degree the following values should be read: $E_{bending} = 9.86$ kcal/mol, $E_{v.d.W.} = 8.36$ kcal/mol, $E_{torsion} = -0.99$ kcal/mol, and $E_{total} = 18.20$ kcal/mol.

Table 3. *MMPI 1 calculated* van der Waals *repulsions [kcal/mol] in dienes* **7** *and* **33**, *triene* **31**, *tetraenes* **3** *and* **32**, *pentaene* **4** *and hexaene* **6**

	Repulsions between 'internal' hydrogen atoms of methylidene groups ($E_{H,H}$)	Repulsions between methylidene carbon atoms ($E_{C,C}$)	$E_{H,H}+E_{C,C}$	Total[a]) *van der Waals* repulsions
7	0.77	0.14	0.91	9.74
33	0.38	0.08	0.46	3.96
31	0.74	0.14	0.88	7.64
3	1.57	0.29	1.86	9.10
32	0.65	0.12	0.77	5.64
4	1.47	0.27	1.74	6.81
6	2.39	0.44	2.83	8.36

[a]) *Van der Waals* 1,3-interactions being neglected [33].

diene moieties (eclipsed conformations). Torsion about the C(2),C(3)-bond of the butadiene unit releaves the *van der Waals* strain but makes the torsional strain increase more rapidly with ω *(Fig. 2)*.

We thank *Hoffmann-La Roche & Co. AG*, Basel, the *Fonds National Suisse de la Recherche Scientifique*, the *Fonds Herbette*, Lausanne, and the *Stipendienfonds der Basler Chemischen Industrie* for generous support.

Experimental Part

General remarks. See [12b]. *Kinetic measurements,* see [9]. *Synthesis of pentamethyl bicyclo[2.2.2]-oct-2-ene-2,5*endo,*6*endo,*7*syn,*8*syn-*pentacarboxylate*[6]) (**12**). An homogeneous mixture of coumalic acid (50 g, 0.36 mol) and maleic anhydride (105 g, 1.07 mol) was heated to 200° (*Bunsen* burner) in a round bottom flask adapted to a vertical pyrex tube (⌀ = 2 cm, l = 30 cm) allowing reflux of the maleic anhydride. The mixture was heated until evolution of CO_2, then the reaction was self-sustained for 1–2 min. After the end of CO_2 evolution, the mixture gave a solid that was triturated with MeOH (2 × 100 ml) to extract the excess of maleic anhydride. The residue was composed of the bis-anhydride **11**, m.p. > 330° (dec.). It was dissolved in 1300 ml MeOH/$CHCl_3$ 850:450 and *p*-toluene-sulfonic acid (50 mg) and heated under reflux in a *Soxhlet* extractor for 6 days (drying agent: molecular sieves 3–4 Å). After evaporation of the solvent, **12** was obtained as a white solid (125 g, 87% from coumalic acid), m.p. 137–138°. – UV. (CH_3CN): 215 (9600). – IR. (KBr): 3010, 2970, 2860, 1740, 1630, 1440, 1390, 1380, 1340, 1320, 1300, 1260, 1240, 1200, 1170, 1115, 1090, 1030, 935, 900. – ^{1}H-NMR. ($CDCl_3$): 7.5 (*d* × *d*, *J* = 7, 1 H, H–C(3)); 3.8 (*m*, 1 H, H–C(4)); 3.75 (*s*, 3 H); 3.60–3.58 (4 *s*, 12 H); 3.5 (*m*, 1 H, H–C(1)); 3.2 (*d* × *d*, *J* = 10 and 2, 2 H, H–C(6), H–C(7)); 3.0 (*d* × *d*, *J* = 10 and 2, 2 H, H–C(5), H–C(8)). – ^{1}H-NMR. (C_6D_6): 7.79 (*d* × *d*, *J* = 7, 1 H); 3.99 (*m*, 1 H); 3.45 (*m*, 1 H); 3.40 (*s*, 3 H); 3.37 (*s*, 6 H); 3.35 (*s*, 6 H); 2.89 (*d* × *d*, *J* = 10 and 2); 2.54 (*d* × *d*, *J*((H–C(7), H–C(8)) = *J*(H–C(5),H–C(6)) = 10, *J*(H–C(8),H–C(4)) = *J*(H–C(5),H–C(4)) = *J*(H–C(1),H–C(1), H–C(6)) = *J*(H–C(1),H–C(7)) = 2, 2 H, H–C(5), H–C(8)). – ^{13}C-NMR. ($CDCl_3$): 171.3 and 171.1 (2 br. *s*, CO); 164.3 (br. *s*, MeOO*C*–C(2)); 140.7 (*d*, ^1J(C,H) = 174, C(3)); 132.6 (*s*, C(2)); 51.4 (*qa*, ^1J(C,H) = 147, *C*H_3OOC at C(5), C(6), C(7) and C(8)); 51.2 (*qa*, ^1J(C,H) = 147, *C*H_3OOC–C(2));

[6]) The term *syn(anti)* means that a substituent on the bridge is located on the same (opposite) side as the C(2),C(3)-branch of the main ring.

45.7 (*s*, ^1J(C,H) = 136, C(5), C(6), C(7) and C(8)); 35.6 and 35.0 (2 *d*, ^1J(C,H) = 143). – MS. (70 eV): 398 (8), 367 (64), 339 (17), 334 (24), 308 (20), 307 (49), 306 (37), 279 (28), 278 (27), 274 (24), 247 (50), 237 (43), 221 (50), 195 (39), 163 (32), 151 (47), 113 (55), 105 (55), 91 (29), 59 (100).

$C_{18}H_{22}O_{10}$ (398.36) Calc. C 54.27 H 5.57% Found C 54.37 H 5.56%

*Synthesis of pentamethyl 8*anti*-cyanobicyclo[2.2.2]octane-2*endo*, 3*exo*, 5*endo*, 6*exo*, 7*syn*-pentacarboxylate*[6]) (**13**). A mixture of **12** (50 g, 0.13 mol), KCN (12.6 g, 0.19 mol), acetone cyanohydrine (12.8 g, 0.15 mol), tetrabutylammonium cyanide (2 g, 0.0075 mol) and anh. CH_3CN (750 ml) was heated to 80° under stirring for 20 h. The solvent was evaporated *i.v.*, the residue dissolved in $CHCl_3$ (300 ml) and washed with H_2O (3 × 100 ml). After drying (Na_2SO_4) and evaporation of the solvent, **13** was obtained as an oil (52 g, 97%) that crystallized with difficulty in MeOH. – UV. (CH_3CN): 215 (350). – IR. (KBr): 3010, 2965, 2860, 2260, 1740, 1440, 1375, 1300, 1250, 1210, 1180, 1060, 1010. – ^{1}H-NMR. ($CDCl_3$): 3.90–3.63 (5 *s*, 15 H); 3.6–2.8 (*m*, 8 H). – MS. (70 eV): 427 (2), 426 (4), 425 (9), 410 (12), 407 (5), 394 (74), 393 (59), 361 (100), 334 (50), 333 (51), 306 (26), 274 (40), 214 (29), 163 (50), 113 (43), 105 (33), 91 (1), 77 (22), 59 (63).

$C_{12}H_{23}NO_{10}$ (425.39) Calc. C 53.65 H 5.45% Found C 53.74 H 5.73%

*Synthesis of hexamethyl bicyclo[2.2.2]octane-2*endo*, 3*exo*, 5*endo*, 6*exo*, 7*syn*, 8*anti*-hexacarboxylate*[6]) (**14**). A mixture of **13** (50 g, 0.12 mol), H_2SO_4 (15 ml) and practical acetic acid (80%, 500 ml) was heated under reflux (130°) for 4 days. After evaporation of the solvent *i.v.*, the residue (oily solid) was dissolved in MeOH (500 ml) and $CHCl_3$ (250 ml), and the mixture was heated under reflux in a *Soxhlet* extractor for 5–7 days (drying agent: molecular sieves 3–4 Å). After evaporation of the solvent, the residue was dissolved in $CHCl_3$ (300 ml) and washed with water (3 × 100 ml). After drying ($MgSO_4$), the solvent was evaporated and the residue recrystallized from MeOH, yielding **14** as a white solid (**46** g, 85%), m.p. 184–185°. – UV. (CH_3CN): 212 (440). – IR. (KBr): 3010, 2960, 2860, 1740, 1440, 1380, 1300, 1250, 1200, 1180, 1120, 1055, 1015, 860. – ^{1}H-NMR. ($CDCl_3$): 3.81 (*s*, 18 H); 3.71 (*s*, 2 H, H–C(1), H–C(4)); 3.13 (*s*, 6 H)[7]). – ^{13}C-NMR. ($CDCl_3$): 172.5 (br. *s*); 52.3 (*qa*, ^1J(C,H) = 147); 40.1 (*d*, ^1J(C,H) = 133, C(2), C(3), C(5), C(6), C(7), C(8)); 33.8 (*d*, ^1J(C,H) = 146, C(1), C(4)). – MS. (70 eV): 458 (3), 427 (4), 426 (33), 394 (73), 395 (18), 367 (14), 366 (15), 335 (4), 334 (4), 307 (8), 306 (5), 275 (5), 274 (4), 249 (4), 248 (3), 247 (11), 221 (17), 195 (9), 189 (9), 163 (30), 105 (22), 91 (15), 59 (100). – MS. (CI., isobutane): 459 (M + 1).

$C_{20}H_{26}O_{12}$ (458.42) Calc. C 52.40 H 5.71% Found C 52.49 H 5.67%

*Synthesis of bicyclo[2.2.2]octane-2*endo*, 3*exo*, 5*endo*, 6*exo*, 7*syn*, 8*anti*-hexamethanol*[6]) (**15**). A solution of **14** (10 g, 0.022 mol) in anh. THF (100 ml) was added dropwise to a vigorously stirred suspension of $LiAlH_4$ (6 g, 0.158 mol) in anh. THF (160 ml), under N_2. The mixture was stirred and heated under reflux for 60 h. After cooling to r.t., water (16 ml) was added dropwise under vigorous stirring. Methanol (100 ml) was added, the mixture was heated to 60°, and the inorg. precipitate was eliminated by warm filtration through silica gel (10 g). The inorg. salts/silica gel were extracted with boiling MeOH (4 × 300 ml). The filtrates were united and evaporated *i.v.* yielding crude **15** that was dissolved in water (50 ml) and filtered slowly through an acid ion exchange resin (*Dowex 50 W X8*, 100/200 mesh). After evaporation of the water *i.v.*, **15** was recrystallized from MeOH, yielding 2.6 g (41%) of a white solid, m.p. 290–294°. – UV. (EtOH/H_2O 95:5): end absorption, 215 (150). – IR. (KBr): 3330, 2960, 2940, 2900, 1480, 1450, 1380, 1350, 1240, 1220, 1140, 1050, 1040, 1000, 980, 885. – ^{1}H-NMR. (D_2O): 3.45 (*m*, 12 H); 1.65 (*m*, 2 H); 1.33 (*m*, 6 H). – ^{13}C-NMR. (D_2O/dioxane): 62.6 (*t*, ^1J(C,H) = 144); 37.1 (*d*, ^1J(C,H) = 126, 6 C); 29.8 (*d*, ^1J(C,H) = 128, 2 C).

$C_{14}H_{26}O_6$ (290.35) Calc. C 57.91 H 9.03% Found C 57.84 H 9.03%

Synthesis of 2*endo*, 3*exo*, 5*endo*, 6*exo*, 7*syn*, 8*anti*-*hexakis(chloromethyl)bicyclo[2.2.2]octane* (**16**). A mixture of **15** (2 g, 6.9 mmol), anh. pyridin (3.3 g, 41.7 mmol) and $SOCl_2$ (6.28 g, 52.8 mmol) was heated to 80° under stirring for 2 h and N_2 pressure. More $SOCl_2$ was added (9.8 g, 82.5 mmol), and the mixture was heated to 80° for 3 h more. After cooling to r.t., the mixture was diluted with

[7]) The absence of J(H–C(1),H–C(2)) is explained by a torsion of the bicyclo[2.2.2]octane skeleton due to repulsions between the ester groups that makes the dihedral angle between H–C(1) and H–C(2) to be near 90°.

CH_2Cl_2 (10 ml) and the excess of $SOCl_2$ destroyed slowly by dropwise addition of water (25 ml). The mixture was extracted with CH_2Cl_2 (3×100 ml). The org. extract was washed with sat. $NaHCO_3$-solution (2×100 ml), then with 1N HCl (2×50 ml) and finally with water (2×50 ml). After drying ($MgSO_4$), the solvent was evaporated and the residue recrystallized from $CHCl_3$, yielding 1.25 g (45%) of a slightly brownish solid, m.p. 178–182°. – UV. (CH_3CN): end absorption, 215 (40). – IR. (KBr): 3000, 2970, 2920, 1460, 1445, 1315, 1300, 1270, 850, 750, 720, 675. – ^{1}H-NMR. ($CDCl_3$): 4.0–3.3 (*m*, 12 H); 2.63 (br. *s*, 2 H); 2.0–1.4 (*m*, 6 H). – MS. (70 eV): 368 (2), 366 (3), 364 (4), 362 (3), 333 (1), 331 (4), 329 (8), 327 (7), 319 (2), 317 (6), 315 (12), 313 (10), 297 (0.1), 295 (3), 293 (7), 291 (7), 283 (0.1), 281 (5), 279 (13), 277 (13), 105 (45), 91 (100).

$C_{14}H_{20}Cl_6$ (401.03) Calc. C 41.93 H 5.03% Found C 41.83 H 5.12%

Synthesis (method A) of [2.2.2]hericene (2,3,5,6,7,8-hexamethylidenebicyclo[2.2.2]octane; **6**). A mixture of **16** (1.2 g, 3.1 mmol), *t*-BuOK (6.7 g, 59.7 mmol) and anh. THF (30 ml) was heated to 50° under stirring and N_2 for 3 days. After cooling to r.t., water (30 ml) was added dropwise and the mixture extracted with pentane (5 times, total 50 ml). The org. extract was dried ($MgSO_4$) and evaporated *i.v.* The residue was purified by column chromatography (hexane) on *Florisil* (5 g) and recrystallized from ether, yielding 0.25 g (46%) of **6** as a white solid, m.p. (under Ar): dec. – UV. (isooctane): 268 *S* (6400), 247 (18500); see [2a] [18]. – IR. (KBr): 3090, 2990, 2960, 1780, 1660, 1640, 1615, 1440, 1425, 1410, 1390, 1370, 1255, 1210, 995, 890. – ^{1}H-NMR. ($CDCl_3$): 5.37 (*s*, 6 H, H of H_2C=, *cis* to C(2),C(3), C(5),C(6), C(7),C(8)), 5.01 (*s*, 6 H, H of H_2C=, correspondingly *trans*); 3.78 (*s*, 2 H, H–C(1), H–C(4)). – ^{13}C-NMR. ($CDCl_3$): 144.4 (br. *s*, H_2C=*C*); 104.8 (*d*×*d*×*d*, ^1J(C,H) = 158 and 160, ^3J(C,H) = 4, H_2C=C); 59.2 (*d*, ^1J(C,H) = 150, C(1), C(4)). – MS. (70 eV): 183 (5), 182 (7), 181 (6), 167 (13), 166 (10), 165 (22), 154 (8), 153 (15), 152 (19), 141 (13), 129 (19), 128 (29), 127 (19), 115 (44), 103 (8), 102 (14), 91 (19), 89 (26), 78 (31), 65 (37), 63 (64), 51 (100), 39 (97).

$C_{14}H_{14}$ (182.27) Calc. C 92.25 H 7.74% Found C 92.24 H 7.81%

Synthesis (method B) of [2.2.2]hericene (**6**) via *partially isomerized precursors.* A mixture of **12** (50 g, 0.13 mol), KCN (12.6 g, 0.19 mol), acetone cyanohydrine (12.8 g, 0.15 mol), tetrabutylammonium cyanide (2 g, 0.0075 mol) and CH_3CN/H_2O 99:1 (750 ml) was heated to 80° under stirring for 4 h. The same workup as for **13** yielded the partially isomerized derivatives **13′** (52 g, 97%) as an oil [^{1}H-NMR. ($CDCl_3$): 3.9–3.6 (*m*, 15 H); 3.6–2.8 (*m*, 8 H)]. This mixture was hydrolyzed and esterified following the same procedure as for **13**→**14**, giving a mixture of hexaesters in 65% yield [^{1}H-NMR. ($CDCl_3$): 3.83–3.65 (*m*, 18 H); 3.35–3.0 (*m*, 6 H)]. Reduction of this mixture following the same procedure as for **14**→**15** yielded a mixture **15′** of partially isomerized hexols in 77% yield after filtration on the acid ion exchange resin and recrystallization from MeOH [^{1}H-NMR. (D_2O): 3.51 (*m*, 6 H); 1.70 (*m*, 2 H); 1.41 (*m*, 6 H)]. Following the procedure given for **15**→**16**, this mixture was transformed into a mixture **16′** of hexachlorides (75%, recrystallization from $CHCl_3$) [^{1}H-NMR. ($CDCl_3$): 4.0–3.3 (*m*, 12 H); 2.68–2.38 (*m*, 2 H); 2.0–1.5 (*m*, 6 H)]. This product (1.2 g, 3.1 mmol) was mixed with *t*-BuOK (6.7 g, 59.7 mmol) in DMF/HMPT 6:1 and heated to 50° under stirring and N_2 for 3 h. After cooling to r.t., water (30 ml) was added dropwise and the mixture extracted with pentane (5×50 ml). The extract was washed with water (3×100 ml), dried ($MgSO_4$) and concentrated by evaporation. It was purified by quick filtration (hexane) on a short column of *Florisil* (3 g) and recrystallization from ether/hexane, yielding 0.452 g (80%; 29% global yield from **12**) of pure **6**.

Synthesis of 9,10,11,12-tetramethylidenetricyclo[6.2.2.0^{2,7}]dodeca-2(7)-ene-4,4,5,5-tetracarbonitrile (**17**; *monoadduct of TCE to* **6**). A mixture of **6** (100 mg, 0.55 mmol), TCE (70 mg, 0.55 mmol) and benzene (2–3 ml) was stirred at 20° for 2 h. After evaporation of the solvent, the residue was treated with warm CH_2Cl_2 (3 ml). The precipitate (bis-adduct **18**) was removed by warm filtration. By cooling the CH_2Cl_2 solution to 0°, the monoadduct **17** precipitated as a white powder (92 mg, 54%), m.p. >200° (dec.). – UV. (CH_3CN): 269 *S* (4400), 257 (8950), 250 (9350), 235 (11350), 226 (13000), 218 (13400); spectrum similar to that of **4** [13a] [18]. – IR. (KBr): 3100, 2990, 2960, 2930, 2260, 1800, 1620, 1445, 1435, 1230, 1170, 900. – ^{1}H-NMR. (CD_3COCD_3): 5.26 (*s*, 4 H); 5.0 (*s*, 4 H); 3.90 (*s*, 2 H); 3.54 (*s*, 4 H). – MS. (70 eV): 310 (70), 296 (20), 283 (4), 258 (95), 232 (20), 231 (21), 218 (19), 217 (20), 182 (55), 181 (50), 167 (100), 154 (60), 130 (80), 115 (81), 91 (25).

$C_{20}H_{14}N_4$ (310.36) Calc. C 77.40 H 4.54% Found C 77.33 H 4.46%

Synthesis of 15,16-dimethylidenetetracyclo[6.6.2.0^{2,7}.0^{9,14}]hexadeca-2(7),9(14)-diene-4,4,5,5,11,11,-12,12-octacarbonitrile (**18**; *bis-adduct of TCE to* **6**)[8]. A mixture of **6** (0.1 g, 0.55 mmol), TCE (0.175 g, 1.4 mmol) and CH_2Cl_2 (2–3 ml) in a sealed pyrex tube was stirred at 50° for 15 h. The bis-adduct **18** precipitated and was collected by filtration. It was washed with CH_2Cl_2 (2 ml) and recrystallized from acetone/MeOH 1:1 giving 0.22 g (91%) of a white powder that was dried under high vacuum to remove all traces of acetone, m.p. >200° (dec.). – UV. (CH_3CN): 252 *S* (4450), 241 *S* (8300), 231 (9800). – IR. (KBr): 3100, 2980, 2930, 2860, 2260, 1800, 1635, 1435, 1365, 1240, 1225, 1165, 895. – ^{1}H-NMR. (CD_3COCD_3): 5.36 (*s*, 2 H); 5.16 (*s*, 2 H); 4.30 (*s*, 2 H); 3.68 (*s*, 8 H). – MS. (70 eV): 438 (100), 436 (8), 310 (38), 309 (35), 295 (99), 232 (70), 115 (95), 91 (35).

$C_{26}H_{14}N_8$ (438.45) Calc. C 71.23 H 3.22% Found C 71.35 H 3.33%

Synthesis of dimethyl 9,10,11,12-tetramethylidenetricyclo[6.2.2.0^{2,7}]dodeca-2(7),4-diene-4,5-dicarboxylate (**20**; *monoadduct of DMAD to* **6**). A mixture of **6** (0.13 g, 0.7 mmol), DMAD (0.1 g, 0.7 mmol) and CH_2Cl_2 (2–3 ml) was stirred at 40° for 16 h. A mixture of monoadduct **20**, bis-adduct **21** and the corresponding aromatized derivatives was obtained. The product **20** was isolated by HPLC. (silica gel, 40 atm, hexane/AcOEt 1:1; then the purification was repeated with hexane/AcOEt 10:1) and crystallized from ether/MeOH 1:1 giving 30 mg (13%) of pure **20** as colourless solid, m.p. >100° (dec.). – UV. (CH_3CN): 270 *S* (4050), 257 (7400), 251 (7550), 235 (8500), 220 (15600), 215 (15900). – IR. ($CHCl_3$): 3095, 2960, 2925, 2880, 2830, 1730, 1650, 1435, 1315, 1265, 1160, 1140, 1100, 1060, 1025, 890. – MS. (70 eV): 324 (11), 293 (33), 292 (100), 291 (22), 277 (10), 265 (6), 239 (13), 233 (12), 205 (28), 191 (32), 165 (25), 153 (39), 152 (41), 115 (22), 91 (17).

$C_{20}H_{20}O_4$ (324.37) Calc. C 74.06 H 6.22% Found C 74.01 H 6.30%

Synthesis of tetramethyl 15,16-dimethylidenetetracyclo[6.6.2.0^{2,7}.0^{9,14}]hexadeca-2(7),4,9(14),11-tetraene-4,5,11,12-tetracarboxylate (**21**; *bis-adduct of DMAD to* **6**). A mixture of **6** (0.05 g, 0.28 mmol), DMAD (0.08 g, 0.56 mmol) and CH_2Cl_2 (2 ml) was stirred at 40° for 16 h. A mixture of the bis-adduct **21** and tris-adduct **22** was obtained. It was separated by TLC. (silica gel, hexane/AcOEt 1:3). After recrystallization from MeOH, **21** was obtained (0.065 g, 51%) as a white powder, m.p. 151–153°. – UV. (CH_3CN): 255 *S* (7000), 245 (10000), 235 (11000). – IR. (KBr): 3090, 3000, 2950, 2880, 2820, 1720, 1645, 1435, 1285, 1190, 1135, 1060, 905, 750. – ^{1}H-NMR. ($CDCl_3$): 4.99 (br. *s*, 2 H); 4.78 (br. *s*, 2 H); 3.74 (*s*, 12 H); 3.53 (br. *s*, 2 H); 3.13 (*s*, 8 H). – MS. (70 eV): 466 (15), 435 (69), 434 (81), 433 (37), 432 (41), 404 (9), 403 (13), 402 (26), 387 (41), 382 (33), 381 (32), 375 (43), 324 (7), 264 (85), 229 (46), 228 (48), 227 (45), 226 (41), 205 (39), 178 (52), 115 (9), 91 (7), 59 (100).

$C_{26}H_{26}O_8$ (466.48) Calc. C 66.94 H 5.61% Found C 66.92 H 5.50%

Synthesis of hexamethyl pentacyclo[6.6.6.0^{2,7}.0^{9,14}.0^{15,20}]icosa-2(7),4,9(14),11,15(20)-17-hexaene-4,5,11,12,17,18-hexacarboxylate (**22**; *tris-adduct of DMAD to* **6**). A mixture of **6** (0.05 g, 0.28 mmol), DMAD (0.195 g, 1.4 mmol) and anh. benzene (1–2 ml) was stirred at 50° for 15 h. After evaporation of the solvent, the residue was recrystallized from MeOH, giving 0.14 g (83%) of pure **22** as white powder, m.p. >100° (dec.). – UV. (CH_3CN): 232 (10800). – IR. (KBr): 3005, 2960, 2880, 2830, 1730, 1690, 1600, 1435, 1270, 1230, 1135, 1110, 1060, 1010, 945, 760. – ^{1}H-NMR. ($CDCl_3$): 3.80 (*s*, 2 H); 3.72 (*s*, 18 H); 3.15 (*s*, 12 H). – MS. (70 eV): 608 (12), 577 (20), 529 (40), 517 (27), 515 (27), 458 (37), 398 (26), 397 (24), 359 (31), 347 (30), 346 (32), 345 (35), 252 (56), 162 (45), 139 (68), 91 (11), 59 (100).

$C_{32}H_{32}O_{12}$ (608.59) Calc. C 63.15 H 5.29% Found C 63.08 H 5.19%

Synthesis of 9,10-dimethylidenetricyclo[6.2.2.0^{2,7}]dodeca-2(7)-ene-4,4,5,5-tetracarbonitrile (**23**; *monoadduct of TCE to* **3**). A solution of TCE (50 mg, 0.39 mmol) in anh. benzene (1–2 ml) was added dropwise to a solution of **3** [6] [13a] (62 mg, 0.39 mmol) in anh. benzene (1–2 ml) cooled to 10°. The yellow colour of the TCE-benzene complex disappeared in a few sec. The mixture was heated to 30° and filtered to eliminate the insoluble bis-adduct **25**. After solvent evaporation, the crude monoadduct **23** was recrystallized from CH_2Cl_2/pentane 1:1 yielding 80 mg (72%) of colourless crystals,

---

[8]) The tris-adduct of TCE to **6** was formed slowly by addition of TCE to a dilute solution of **18** in CH_2Cl_2 (40°) giving a white powder that was insoluble in most solvents and could not be volatilized in the MS. spectrometer. This powder decomposed upon heating above 200°.

m.p. 200° (dec.). – UV. (CH_3CN): 259 *S* (4400), 247 (8100), 241 (8400), 230 (7450). – IR. (KBr): 3100, 3000, 2960, 2940, 2920, 2880, 2260, 1780, 1625, 1465, 1440, 1235, 885. – ^{1}H-NMR. (CD_3COCD_3): 5.20 (*s*, 2 H); 4.84 (*s*, 2 H); 3.49 (*s*, 4 H); 3.24 (*m*, 2 H); 1.8–1.5 (*m*, 4 H). – MS. (70 eV): 286 (17), 259 (20), 258 (100), 193 (5), 192 (6), 166 (15), 130 (43), 129 (17), 128 (15), 115 (23), 91 (3).

$C_{18}H_{14}N_4$ (286.33) Calc. C 75.80 H 5.05% Found C 75.51 H 4.93%

Synthesis of tetracyclo[6.6.2.0^{2,7}.0^{9,14}]hexadeca-2(7),9(14)-diene-4,4,5,5,11,11,12,12-octacarbonitrile (**25**; *bis-adduct of TCE to* **3**). A mixture of **3** (57 mg, 0.36 mmol) and TCE (138 mg, 1.08 mmol) in CH_2Cl_2 (5 ml) was stirred at 40° for 15 h. The bis-adduct **25** precipitated; it was filtered off and washed successively with benzene (5 ml) and CH_2Cl_2 (2 ml). After recrystallization from acetone/hexane 1:1, 120 mg (80%) of white crystals were obtained, m.p. >200° (dec.). – UV. (CH_3CN): end absorption, 215 (2000). – IR. (KBr): 2970, 2880, 2260, 1435, 1360, 1240, 1220, 1155, 1085. – ^{1}H-NMR. (CD_3COCD_3): 3.63 (br. *s*, 2 H); 3.53 (*s*, 8 H); 1.53 (br. *s*, 4 H). – MS. (70 eV): 386 (20), 359 (2), 333 (1), 306 (12), 259 (23), 258 (100), 166 (8), 130 (10), 115 (10), 91 (2).

$C_{24}H_{14}N_8$ (414.42) Calc. C 69.56 H 3.40% Found C 69.43 H 3.61%

Synthesis of 11,12-dimethylidenetricyclo[6.2.2.0^{2,7}]dodeca-2(7),9-diene-4,4,5,5-tetracarbonitrile (**24**; *monoadduct of TCE to* **4**). A mixture of **4** [6] [13a] (197 mg, 1.26 mmol) and TCE (160 mg, 1.25 mmol) in anh. benzene (10 ml) was stirred at 20° for 15 h. The monoadduct **24** precipitated at +10°; it was filtered off and washed with cold benzene (1–3 ml). After recrystallization from CH_2Cl_2/pentane 1:1, 310 mg (87%) of colourless crystals were obtained, m.p. >200° (dec.). – UV. (CH_3CN): 257 *S* (3600), 243 *S* (8400), 236 (9100). – IR. (KBr): 3100, 3090, 3000, 2960, 2920, 2260, 1790, 1645, 1630, 1600, 1440, 1430, 1230, 1170, 905, 890, 805. – ^{1}H-NMR. (CD_3COCD_3): 6.36 (*d*×*d*, *J*=3.0 and 4.0, 2 H); 5.13 (*s*, 2 H); 4.86 (*s*, 2 H); 3.88 (*d*×*d*, *J*=3.0 and 4.0, 2 H); 3.19 (*s*, 4 H). – MS. (70 eV): 284 (27), 258 (1), 257 (3), 256 (2), 230 (2), 205 (8), 191 (8), 156 (57), 141 (100), 128 (50), 115 (16), 91 (4), 52 (75).

$C_{18}H_{12}N_4$ (284.32) Calc. C 76.04 H 4.25% Found C 76.14 H 4.24%

Synthesis of tetracyclo[6.6.2.0^{2,7}.0^{9,14}]hexadeca-2(7),9(14),15-triene-4,4,5,5,11,11,12,12-octacarbonitrile (**26**; *bis-adduct of TCE to* **4**). A mixture of **4** (150 mg, 0.96 mmol) and TCE (370 mg, 2.9 mmol) in CH_2Cl_2 (5 ml) was stirred at 40° for 15 h. The bis-adduct **26** was filtered off and washed successively with benzene (5 ml) and CH_2Cl_2 (2 ml). After recrystallization from acetone/hexane 1:1, 375 mg (95%) of colourless crystals were obtained, m.p. 200° (dec.). – UV. (CH_3CN): 234 (2250). – IR. (KBr): 3090, 3005, 2980, 2960, 2930, 2260, 1595, 1440, 1365, 1305, 1220, 970, 830, 825, 665. – ^{1}H-NMR. (CD_3COCD_3): 6.89 (*d*×*d*, *J*=3.0 and 4.0, 2 H); 4.71 (*d*×*d*, *J*=3.0 and 4.0, 2 H); 3.62 (*m*, 8 H). – MS. (70 eV): 412 (53), 284 (59), 157 (100), 141 (57), 128 (32), 115 (27), 91 (12).

$C_{24}H_{12}N_8$ (412.41) Calc. C 69.89 H 2.93% Found C 69.83 H 3.14%

REFERENCES

[1] *J.-P. Hagenbuch, J.-L. Birbaum, J.-L. Métral & P. Vogel*, Helv. Chim. Acta *64*, 887 (1982).

[2] a) *O. Pilet & P. Vogel*, Angew. Chem. Int. Ed. *19*, 1003 (1980); b) *L. de Piccioto, P.-A. Carrupt & P. Vogel*, J. Org. Chem. *47*, 3796 (1982).

[3] a) *M. Mohraz, C. Batich, E. Heilbronner, P. Vogel & P.-A. Carrupt*, Recl. Trav. Chim. Pays-Bas *98*, 361 (1979); b) *M. Mohraz, W. Jian-qi, E. Heilbronner, P. Vogel & O. Pilet*, Helv. Chim. Acta *63*, 568 (1980); c) *W.T. Borden, S.D. Young, D.C. Frost, N.P.C. Westwood & W.L. Jorgensen*, J. Org. Chem. *44*, 737 (1979); *P. Bischof, R. Gleiter & R. Haider*, Angew. Chem. *89*, 112 (1977); *iidem*, J. Am. Chem. Soc. *100*, 1036 (1978); *L. Paquette, R.V.C. Carr, M.C. Böhm & R. Gleiter*, ibid. *102*, 1186 (1980); d) *H.-U. Pfeffer, M. Klessinger, G. Erker & W.R. Roth*, Chem. Ber. *108*, 2923 (1975); e) *H.-U. Pfeffer & M. Klessinger*, Org. Magn. Reson. *9*, 121 (1977); *D. Quarroz, J.-M. Sonney, A. Chollet, A. Florey & P. Vogel*, Org. Magn. Reson. *9*, 611 (1977); *V. Gergely, Z. Akhavin & P. Vogel*, Helv. Chim. Acta *58*, 871 (1975); f) *P. Asmus & M. Klessinger*, Tetrahedron *30*, 2477 (1974); g) *P.V. Alston & R.M. Ottenbrite*, J. Org. Chem. *41*, 1635 (1976); *iidem*, ibid. *40*, 322 (1975).

[4] *D.N. Butler & R.A. Snow*, Can. J. Chem. *53*, 256 (1975); *iidem*, ibid. *52*, 447 (1974); *iidem*, ibid. *50*, 795 (1972); *W.T. Borden & A. Gold*, J. Am. Chem. Soc. *93*, 3830 (1971); *W.L. Jorgensen & W.T. Borden*, ibid. *95*, 6649 (1973); *L.W. Jelinsky & E.F. Kiefer*, ibid. *98*, 281, 282 (1976); *H. Hogeveen, W.F.J. Huurdeman & D.M. Kok*, ibid. *100*, 871 (1978).
[5] *M. Avenati, J.-P. Hagenbuch, C. Mahaim & P. Vogel*, Tetrahedron Lett. *1980*, 3167.
[6] *R. Gabioud & P. Vogel*, Tetrahedron *36*, 149 (1980).
[7] *A. Chollet, C. Mahaim, C. Foetisch, M. Hardy & P. Vogel*, Helv. Chim. Acta *60*, 59 (1977).
[8] *M. Hardy, P.-A. Carrupt & P. Vogel*, Helv. Chim. Acta *59*, 936 (1975).
[9] *O. Pilet, A. Chollet & P. Vogel*, Helv. Chim. Acta *62*, 2341 (1979).
[10] *O. Pilet & P. Vogel*, Helv. Chim. Acta *64*, 2563 (1981).
[11] a) *P. Vogel & A. Florey*, Helv. Chim. Acta *57*, 200 (1974); b) *C. Mahaim, P.-A. Carrupt, J.-P. Hagenbuch, A. Florey & P. Vogel*, ibid. *63*, 1149 (1980).
[12] a) *P.-A. Carrupt & P. Vogel*, Tetrahedron Lett. *1979*, 4533; b) *Y. Bessière & P. Vogel*, Helv. Chim. Acta *63*, 232 (1980); c) *J. Tamariz & P. Vogel*, in preparation.
[13] a) *A. Chollet, M. Wismer & P. Vogel*, Tetrahedron Lett. *1976*, 4271; b) *Ph. Narbel, T. Boschi, R. Roulet, P. Vogel, A.A. Pinkerton & D. Schwarzenbach*, Inorg. Chim. Acta *36*, 161 (1979).
[14] *O. Diels & K. Alder*, Justus Liebigs Ann. Chem. *490*, 257 (1931).
[15] *T. Spoormaker & M.J.A. de Bie*, Recl. Trav. Chim. Pays-Bas *98*, 59, 380 (1979); *P.E. Hansen*, Progr. NMR. Spectrosc. *14*, 175 (1981); *A. Chollet, J.-P. Hagenbuch & P. Vogel*, Helv. Chim. Acta *62*, 511 (1979).
[16] *F. Iordache, F. Chiraleu & M. Avram*, Rev. Roum. Chim. *20*, 233 (1975); Chem. Abstr. *83*, 57812j (1975).
[17] *C.L. Liotta, A.M. Dabdoub, L.H. Zalkow*, Tetrahedron Lett. *1977*, 117.
[18] *C. Sandorfy, P. Mercier, A.A. Pinkerton, D. Schwarzenbach, O. Pilet & P. Vogel*, in preparation.
[19] *D.L.F. De Tar*, 'Computer Programmes for Chemistry', Academic Press (1972); see also: *G. Peckham*, Computer J. *13*, 418 (1970).
[20] *R. Sustmann*, Tetrahedron Lett. *1971*, 2721.
[21] *M. Avenati, O. Pilet, P.-A. Carrupt & P. Vogel*, Helv. Chim. Acta *65*, 178 (1982).
[22] a) *C. Rücker, D. Lang, J. Sauer, H. Friege & R. Sustmann*, Chem. Ber. *113*, 1663 (1980); b) *H.-D. Scharf, H. Plum, J. Fleischhauer & W. Schleker*, ibid. *112*, 862 (1979); *R. Sustmann, M. Böhm & J. Sauser*, ibid. *112*, 883 (1979).
[23] *D. Craig, J.J. Shipman & R.B. Fowler*, J. Am. Chem. Soc. *83*, 2885 (1961); *P.D. Bartlett, G.E.H. Wallbillich, A.S. Wingrove, J.S. Swenton, L.K. Montgomery & B.D. Kramer*, ibid. *90*, 2049 (1968).
[24] *G. Klopman*, J. Am. Chem. Soc. *90*, 223 (1968); *L. Salem*, ibid. *90*, 543, 553 (1968); *K. Fukui*, Acc. Chem. Res. *4*, 57 (1971); Bull. Chem. Soc. Jpn. *39*, 498 (1966); *I. Fleming*, 'Frontier Orbitals and Organic Chemical Reactions', Wiley 1976; *R. Sustmann*, Pure Appl. Chem. *40*, 569 (1974).
[25] *K.N. Houk & L.L. Munchhausen*, J. Am. Chem. Soc. *98*, 937 (1976); *J. Sauer & R. Sustmann*, Angew. Chem. Int. Ed. *19*, 779 (1980).
[26] *J.-P. Hagenbuch, P. Vogel, A.A. Pinkerton & D. Schwarzenbach*, Helv. Chim. Acta *64*, 1818 (1981); A.A. Pinkerton, D. Schwarzenbach, J.H.A. Stibbard, P.-A. Carrupt & P. Vogel, J. Am. Chem. Soc. *103*, 2095 (1981); *W.H. Watson, J. Galloy, P.D. Bartlett & A.A.M. Roof*, J. Am. Chem. Soc. *103*, 2022 (1981).
[27] *O. Dimroth*, Angew. Chem. *46*, 571 (1933).
[28] *A. Pross & S.S. Shaik*, J. Am. Chem. Soc. *104*, 1129 (1982); *S.S. Shaik & A. Pross*, ibid. *104*, 2708 (1982) and ref. therein.
[29] *H.E. Zimmermann & R.M. Paufler*, J. Am. Chem. Soc. *82*, 1514 (1960); *C.W. Jefford, T.W. Wallace & M. Acar*, J. Org. Chem. *42*, 1654 (1977); *G. Taylor*, ibid. *37*, 2904 (1972).
[30] *J.L. Jensen*, Progr. Phys. Org. Chem. *12*, 189 (1976); *R.B. Turner*, J. Am. Chem. Soc. *86*, 3586 (1964); *R.B. Turner, W.R. Meador & R.E. Winkler*, ibid. *79*, 4116 (1957).
[31] *E. Haselbach, E. Heilbronner & G. Schröder*, Helv. Chim. Acta *54*, 153 (1971).
[32] *J.D. Cox & G. Pilcher*, 'Thermochemistry of Organic and Organometallic Compounds', Academic Press, New York 1970.
[33] *N.L. Allinger & J.T. Sprague*, J. Am. Chem. Soc. *95*, 3893 (1973); *J. Kao & N.L. Allinger*, ibid. *99*, 975 (1977); *N.L. Allinger & J.T. Sprague*, Tetrahedron *31*, 21 (1975); QCPE program No. 318.
[34] *H.-U. Pfeffer & M. Klessinger*, Chem. Ber. *112*, 890 (1979).