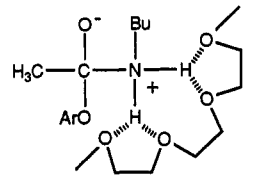
the formation (by either alternative) of *complexed* $T^{\pm}$. How the product forms is also uncertain, but there are two likely possibilities. One is a stepwise process where complexed $T^{\pm}$ decomposes to a tight ion pair (aryloxide and complexed N-protonated amide)[17] followed by a proton transfer to give a phenol and the amide. The other, a concerted path, avoids the tight ion pair. In other words, glyme shuttles a proton[18] from the ammonium ion to the aryl oxide.

Host-Guest Interaction. The optimal catalysis by an $-OCH_2CH_2OCH_2CH_2OCH_2CH_2O-$ subunit implies a specific host-guest interaction between a glyme and the rate-limiting transition structure. We propose a complex, $CT^{\pm}$, in which four oxygens donate electron density to



$CT^{\pm}$

stabilize both hydrogens of the ammonium ion part of $T^{\pm}$. Given the size of the $-{}^{+}NH_2-$ fragment, four oxygens are probably the maximum that can bind it. We offer that the guest transition structure organizes the host. This organization results in *transition-structure recognition* by the host. The imprint left by a transition structure in a flexible host reveals a part of the structure of the guest.

(17) Perrin, C. L. *Acc. Chem. Res.* **1989**, *22*, 268-275.
(18) We thank a reviewer of a previous version of this manuscript for this suggestion.

Conclusions

Glymes catalyze butylaminolysis of aryl acetates in chlorobenzene by binding to the ammonium ion part of $T^{\pm}$ formed by attack of butylamine on the ester. The $-OCH_2CH_2OCH_2CH_2OCH_2CH_2O-$ subunit is optimal for this binding interaction. The binding interaction accelerates the breakdown of $T^{\pm}$ by weakening the bond to the aryloxy group as seen by an increase in ρ with increasing catalysis. The relationship between catalysis and subunit structure suggests that the ammonium ion part of the transition structure is recognized by the catalyst. Studies are in progress to uncover the details of this recognition.

Acknowledgment. We thank Mr. Don Patterson for technical assistance and the Research Corporation for the initial support of this work. We dearly thank Mrs. Mary Jane Peters for her assistance and encouragement.

Supplementary Material Available: Observed rate constants for uncatalyzed and oligoglyme-catalyzed butylaminolysis of substituted phenylacetates at 25 °C in chlorobenzene (32 pages). Ordering information is given on any current masthead page.

The Synthesis of 2,3,3a,4,5,7a-Hexahydro-1*H*-inden-1-ols by Intramolecular Diels-Alder Reactions of 1,3,8-Nonatrien-5-ols. Dependence of Product Stereochemistry on the Substitution Pattern

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Received July 16, 1990

A short and efficient synthesis of the title compounds is described, starting from readily available α,β-unsaturated carbonyl compounds **5** and β,γ-unsaturated ketones **4**. Their directed aldol condensation yields the unsaturated hydroxy ketones **6** which are dehydrated to the trienones **7**. Athough these fail to cyclize on heating, the intramolecular Diels-Alder reaction can be brought about after reduction or alkyllithium addition to the carbonyl group. Alkyl substitution in the positions 1, 2, 3, 5, and 7 has little influence on the ease and yield of cyclization, whereas a methyl group at C-4 hinders it considerably. The title compounds are obtained as mixtures of usually all four stereoisomers, of which one predominates (≥50%) in most cases. O-Alkylation in **8b** has little effect on the isomer distribution. The major isomer of the 6-bromo derivative forms a highly crystalline *p*-nitrobenzoate **27**, which permits stereochemical assignment through X-ray crystallography; for most other products assignments can be made by comparison and further evaluation of their ^1H NMR spectra. The results are discussed in terms of a simple transition state model. The intramolecular Diels-Alder reaction fails when the length of the tethering chain is reduced by one, or when the diene unit becomes part of a furan ring. Trienones **7** are sensitive to autoxidation, of which some products are described.

The intramolecular Diels-Alder reaction is a powerful tool of organic synthesis,[1] although stereoselectivity is often moderate. In the course of a larger synthetic project, we needed a simple and efficient access to 2,3,3a,4,5,7a-hexahydro-3,3-dimethyl-1*H*-inden-1-ol, **18b**. The relative stereochemistries at C-1/C-7a and C-3a/C-7a were not a major issue because C-1 would later be oxidized to the ketone and C-7a subjected to epimerization. It appeared therefore promising to procure **18b** by an intramolecular Diels-Alder ring closure of its open-chain isomer **17b**, the corresponding ketone **7b**, or protected derivatives thereof. While the preparation of the triene precursors may be cumbersome in other cases, **7b** ought to be accessible by dehydration of the aldol **6b**, and this in turn through directed aldol addition[2] of the kinetic enolate of the known[3]

(1) (a) Brieger, G.; Bennett, J. N. *Chem. Rev.* **1980**, *80*, 63. (b) Ciganek, E. *Org. React.* **1984**, *32*, 1. (c) Taber, D. F. *Intramolecular Diels-Alder and Alder Ene Reactions*; Springer: New York, 1984. (d) Fallis, A. G. *Can. J. Chem.* **1984**, *62*, 1831. (e) Salakhov, M. S.; Ismailov, S. A. *Russ. Chem. Rev.* **1986**, *55*, 1145. (f) Roush, W. R. *Advances in Cycloaddition*; Curran, D. P., Ed.; JAI Press: Greenwich, 1990; Vol. 2, pp 91-146.

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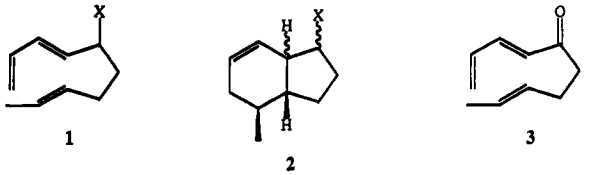
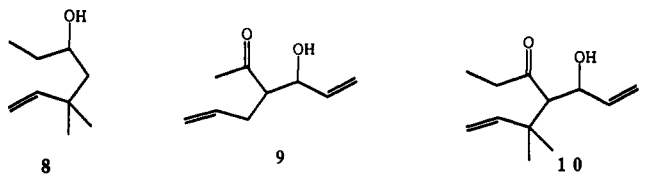
Scheme I



a X = OH
b X = OSi(*t*-Bu)Me$_2$

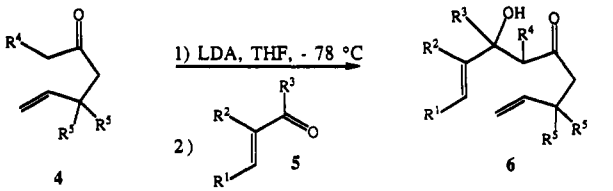
and easily prepared ketone **4b** to acrolein **5a**. As for the Diels–Alder reaction itself, precedent was available from the work of Oppolzer et al.[4] who cyclized, although with some difficulty, the trienol **1a** to the hexahydroindenol **2a** through intermediacy of the silyl derivatives **1b** and **2b**. On the other hand, two representatives of 1,3,8-nonatrien-5-ones, **3** and **7a**, were reported not to undergo the reaction.[4,5] Whereas the methyl group in **1** clearly has an adverse effect on cyclization, the *gem*-dimethyl group in **7b** and **17b** might either act favorably through its *gem*-dialkyl effect[6] or adversely due to its proximity to the dienophilic double bond. Since the presence of a quaternary sp^3 carbon atom directly adjacent to a nonactivated C=C double bond intended to act as a dienophile is unusual (no simple acyclic substrates of this kind have been investigated to the best of our knowledge), an attempt was all the more worthwhile. The unexpected ease with which this reaction took place provided us impetus to study a few more examples to probe its generality. The requisite intermediates were synthesized in analogy to the considerations outlined for **17b** (Scheme I), and the individual steps are discussed in the following section.

Aldol Condensation. Little difficulty was anticipated in generating the kinetic enolate from **4b**, and indeed the ^{1}H and ^{13}C NMR spectra of the derived aldols give no indication of a contamination by regioisomers. On the other hand, the outcome was less predictable in the case of **4a** (with reduced steric hindrance at the undesired deprotonation site) and **4c** (with increased hindrance at the desired site). In the event, reaction of **4a** with acrolein produced a 6:1 mixture of **6a** with its isomer **9** if lithium diisopropylamide (LDA) was used as the base, or 8:1 with the more hindered lithium 2,2,6,6-tetramethylpiperidide (LTMP) (Scheme II). The difference hardly exceeds the integration error and does not justify the use of the more expensive LTMP. Reaction of **4c** with acrolein gave **6g** containing approximately 3% of an impurity which is probably the regioisomer **10**, but the impurity could not



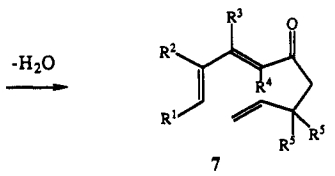
be identified with certainty due to extensive signal overlap in the ^{1}H NMR spectrum. These mixtures were inseparable and had to be carried through the next step. ^{1}H and ^{13}C NMR spectra of the aldols **6** and the derived trienones

Scheme II



4	R^4	R^5
a	H	H
b	H	Me
c	Me	Me

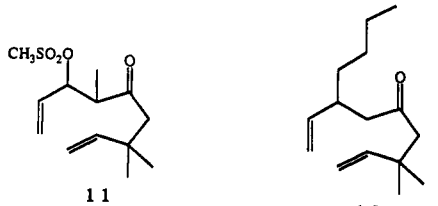
5	R^1	R^2	R^3
a	H	H	H
b	H	Me	H
c	$(CH_2)_3$		H
d	H	Br	H
e	H	H	Me



6,7	R^1	R^2	R^3	R^4	R^5
a	H	H	H	H	H
b	H	H	H	H	Me
c	H	Me	H	H	Me
d	$(CH_2)_3$		H	H	Me
e	H	Br	H	H	Me
f	H	H	Me	H	Me
g	H	H	H	Me	Me

7 and trienols **17** are summarized in Tables III and IV.

Dehydration and Reduction. Among the four methods attempted to effect dehydration of **6**, none was satisfactory in all cases. Refluxing **6b** and **6f** with pyridinium *p*-toluenesulfonate (PPTS) under a water separator (method A) gave fair yields of the trienones, but also some **6b** was recovered at a point where the reaction did not seem to proceed further and polymerization became competitive. Treatment with methanesulfonyl chloride and 3 equiv of triethylamine (method B) gave good yields (75–85%) of **7b–e**, the intermediate aldol mesylates undergoing elimination in situ by the excess of the base. The product **7a** obtained in this way tended to polymerize violently during distillation, as did the derived alcohol **17a** if crude **7a** was immediately subjected to reduction. This problem was solved by using trifluoromethanesulfonic anhydride instead of mesyl chloride and working at low temperatures (method C); still the yield of **7a** is moderate. Trienone **7g** was best prepared by mesylation of **6g** to obtain a quantitative yield of **11** which is stable to triethylamine under the above conditions, but easily eliminates methanesulfonic acid on action of DBU (method D).



(2) (a) Stork, G.; Kraus, G. A.; Garcia, G. A. *J. Org. Chem.* **1974**, *39*, 3459. (b) Smith, A. B., III; Levenberg, P. A. *Synthesis* **1981**, 567.
(3) House, H. O.; Chu, C.-Y.; Phillips, W. V.; Sayer, T. S. B.; Yan, C.-C. *J. Org. Chem.* **1977**, *42*, 1709.
(4) Oppolzer, W.; Fehr, C.; Warneke, J. *Helv. Chim. Acta* **1977**, *60*, 48.
(5) Bloch, R.; Abecassis, J.; Hassan, D. *Can. J. Chem.* **1984**, *62*, 2019.
(6) (a) Allinger, N. L.; Zalkov, V. *J. Org. Chem.* **1960**, *25*, 701. (b) Sternbach, D. D.; Rossana, D. M.; Onan, K. D. *Tetrahedron Lett.* **1985**, *26*, 591.

Table I. Intramolecular Diels–Alder Reactions of 17 and 22

starting material	scale (mmol)	temp (°C)	time (h)	product	yield (%)	ratio of stereoisomers[a]
17a	4	180	18	**18a**	70	15:20:50:15
17b	0.26	155	215	**18b**	*b*	10:18:55:17
	10	185	7		93	14:23:46:17
	0.28	260	0.5		96	12:25:43:20
17c	18	185	7	**18c**	57	12:19:50:19
17d	0.2	200	7.5	**18d**	94	10:16:59:15
17e	1.3	190	9	**18e**	47	16:24:47:13
17f	1.7	190	26	**18f**	81[c]	0:7:23:70
17g	0.2	270	120	**18g**	13	*d*
17h	0.32	190	8	**18h**	65[e]	32:44:11:13
22a	0.63	180	11.5	**23a**	81	12:13:55:20
22b	0.16	185	6.5	**23b**	94	11:16:52:21

[a] Cis-endo/trans-endo/cis-exo/trans-exo. [b] Not determined. [c] Including the recovered *Z* isomer of the starting material. [d] See text. [e] Overall yield from **7h**.

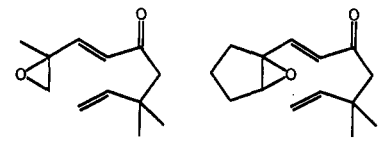
Surprisingly, products derived from the "wrong" aldols **9** and **10** were not found. This is possibly the result of steric hindrance either in the sulfonylation or the subsequent elimination step in these branched molecules, and unreacted starting material or its sulfonate is then removed during chromatography. Whatever the reason, we were pleased to obtain **7a** and **7g** free from their regioisomers.

If the C(3)=C(4) double bond is not alkylated, it has exclusively *E* configuration within the limits of NMR detection. Trienone **7f** is formed as an approximate 2:1 mixture of *E* and *Z* isomers. The *Z* isomer is recognized by strong deshielding of 2-H (δ = 7.68 in comparison with 6.35 for the *E* isomer and 6.44 for **7b**) as a consequence of its proximity to the anisotropic carbonyl group. Compound **7g** is homogeneous within the limits of NMR detection, and the absence of an unusual deshielding of 2-H (δ = 6.73) characterizes its configuration as *E*.

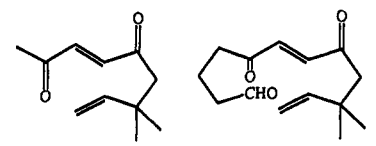
Reduction of the trienones **7a–g** to the corresponding trienols **17a–g** proceeded uneventfully by means of $LiAlH_4$ in THF. In the case of **7b**, addition of *n*-butyllithium produced the tertiary alcohol **17h** and the 1,4-addition product **12** in an approximate 10:1 ratio.

Stability of the Trienones 7. All of the trienones **7** prepared in this work except for the bromo derivative **7e** are distillable yellow liquids, which can be handled without special precautions but are sensitive to polymerization and/or autoxidation on extended storage even at low temperatures and in the dark. Trienone **7e** has an exceptional tendency to polymerize and had to be processed further in solution (see the Experimental Section). The compound exhibiting the next highest polymerizability is the parent trienone **7a**, a sample of which was found to have solidified to a granular resin after several months at −15 °C. Trienone **7b** reproducibly exhibited peaks up to $(2M)^+$ (*m/z* 328) in the mass spectrum after standing at 0–5 °C for a few days only, but the bulk sample remained liquid and for the major part unchanged after one year at −15 °C.

Derivatives alkylated in the diene moiety polymerize less readily, and autoxidation becomes the favored pathway of decomposition. This is of little consequence for bulk samples in tightly closed vials, but a backlog in our mass spectrometry facility gave us the opportunity to observe this reaction which would otherwise have escaped our attention. Small samples of **7c** and **7d** set aside in comparatively large vials under an ordinary atmosphere at 0–5 °C gave mass spectra after approximately 8 weeks (subsequent deliberate oxidation experiments showed that half of this time is sufficient) which did not exhibit the expected molecular ions but instead $(M + 2)^+$ in the case of **7c** and $(M + 32)^+$ in the case of **7d**. NMR spectroscopy (see the Experimental Section) indicated that in both cases the mixture consists predominantly of one product to which we assign the structure of a monoepoxide (**13** and **14**, respectively). Formation of such epoxides has previously been observed in the autoxidation of conjugated dienones at elevated temperatures,[7] but the occurrence of this reaction near 0 °C is somewhat surprising. Attempted purification by column chromatography in both cases resulted largely in decomposition, but the more stable minor products **15** and **16** could be isolated. They result (by an unknown pathway) from an ozonolysis-like oxidative cleavage of the (C-1)=(C-2) double bond (one carbon atom being lost, probably as CH_2O, in the former case) and account for the observed mass spectra. In conclusion, it is advisable to process the trienones **7** with as little delay as possible.



13 14

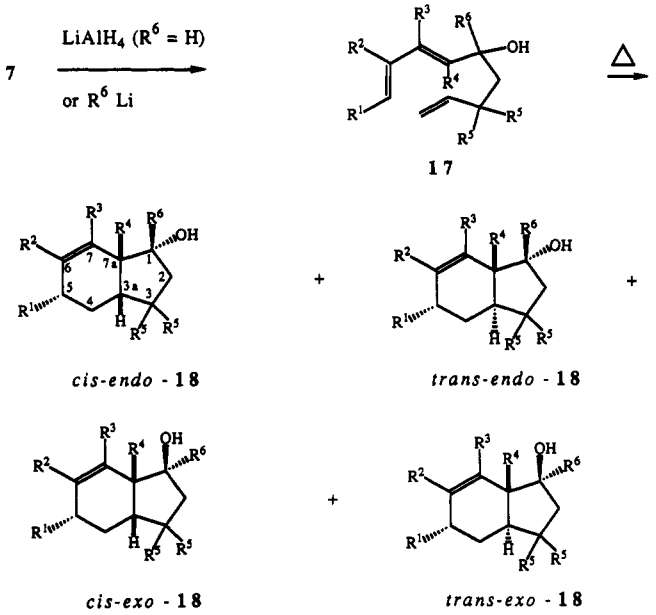


15 16

Diels–Alder Reactions. In line with precedent,[4,5] **7b** did not undergo an intramolecular Diels–Alder reaction on heating. At 180 °C in chlorobenzene (*c* = 0.06 M) for 3.5 h, a complex mixture was formed whereas no reaction occurred in boiling toluene. Two equivalents of $BF_3{\cdot}OEt_2$ in 1,2-dichloroethane failed to induce a reaction at 0 °C, and caused decomposition at 60 °C, which also occurred with 2 equiv of $SnCl_4$ in the same solvent at 0 °C. Attention was therefore turned to the alcohol **17b**, which indeed cyclized efficiently at 185 °C in chlorobenzene. It is remarkable that no elimination resulting from surface-catalyzed generation of a carbenium ion could be observed, although the latter is stabilized by the conjugated double bonds. Alkylation of the diene moiety, however, facilitates ionization sufficiently to become a serious side reaction. The products **18c,d** were thus obtained in only 57 and 14% yield, and the tetraene **19** was detected along with **18c**. The simple precaution of washing the reaction vessel with alkali and adding a small amount of tributylamine suppressed this side reaction and increased the yield of **18d** to 94%. Further examples (Table I) were therefore generally conducted in this way which, although perhaps unnecessary in some cases, does in no instance seem to cause

(7) Hart, H.; Lavrik, P. B. *J. Org. Chem.* **1974**, *39*, 1793.

Scheme III



17,18	R^1	R^2	R^3	R^4	R^5	R^6
a-g	---------- as for 6,7 ----------					H
h	H	H	H	H	Me	*n*-Bu

any harm; even the tertiary alcohol **17h** could be cyclized in fair yield. The examples demonstrate that alkylation at C-1,2,3,5 does not significantly affect the ease of cyclization, and the successful preparation of **18a** rules out a significant contribution of the "*gem*-dialkyl effect" to the free energy balance of the reaction. An example (**28**) has been published in which the effect of a *gem*-dimethyl group was insufficient to overcome the unreactivity of a triene, but the cyclization became feasible on replacement of methyl with larger groups.[6b] In the case of **17f** only the *E* isomer reacts; it would have been interesting to attempt the cyclization of *Z*-**17f** at higher temperatures, but unfortunately neither the *E*/*Z* mixture itself nor (after cyclization) the mixture of *Z*-**17f** with one of the product stereoisomers could be separated. The bromo substituent in **17e** imparts on the compound a tendency for polymerization which resulted, contrary to the above examples, in a dark crude product and low yield; addition of hydroquinone as a polymerization inhibitor made things worse (possibly because of its acidity). The most recalcitrant substrate was **17g**, which cyclized only at 270 °C and then in very poor yield, most of the material being lost by decomposition. Others[4] used silylation in a similar case to improve stability; this proved helpful here, too. Thus, the *tert*-butyldimethylsilyl ether **20** afforded **21** at 260 °C (48 h) containing approximately 6% of starting material (total recovery: 46%). The benzyl ether **22a** and the *tert*-butyldiphenylsilyl ether **22b** of **17b** cyclized uneventfully to **23a,b**.

Stereochemistry. The subsequent discussion follows well-established lines.[1b] Depending on whether the bond between the tethering chain and the dienophile is located on the same or opposite side relative to the inner carbon atoms of the diene moiety, intramolecular Diels–Alder reactions may proceed through syn (**24**) or anti (**25**) transition states, leading to cis- and trans-fused ring systems, respectively. In order to evaluate the possible influence of substituents on the stereochemical outcome, it is necessary to know the result for the parent compound and to consider interactions between the substituents. Cyclization of the parent hydrocarbon, 1,3,8-nonatriene,[8] furnishes a 3:1 mixture of the *cis*- and *trans*-hexahydroindenes. Since the hydroxyl function is free to adopt the less hindered position, and the *gem*-dimethyl group, too, interacts little with other groups if $R^{3,4}$ = H, we expected to find similarly a predominance of cis-fused products among **18a–e**. To predict the preferential orientation of the hydroxyl group, one might consider to use 3-buten-2-ol as a model for the C(3)–C(4)–C(5)–C(6) segment; it has, however, been reported[9] that the energy differences among its preferred conformers are small (the conformer roughly corresponding to **24**, **25** with X^1 = H, X^2 = OH being slightly favored). If R^3 or R^4 is not hydrogen, steric interactions emerge between these groups and the *gem*-dimethyl group. Thus R^3 = Me destabilizes the syn, and R^4 = Me the anti transition state, which allows to predict that **18f** should exhibit a reduced, and **18g** an increased cis/trans ratio in comparison with **18b**. Furthermore, in both transition states for the cyclization of **18f** there is a repulsion between R^3 = Me and the hydroxyl group if the latter occupies the position of X^1; consequently the predominant formation of exo alcohols (X^2 = OH) is expected. Finally, for **17h** the decisive interaction is that between the C(3)=C(4) double bond and the roughly eclipsing substituent X^1. Since butyl is larger than OH (or, to use 3-buten-2-ol as a model: eclipsing of vinyl and OH is observed, but not of vinyl and methyl), the preferential formation of endo alcohols (X^1 = OH) is predicted. Nothing can be said in this case about the cis/trans ratio.

The experiment delivered the cyclization products as mixtures of all four or, in the case of **18f,g**, three diastereoisomers. The ^{1}H NMR spectra of these mixtures are necessarily complex, but nevertheless reveal some important features. The signals of the α-protons (1-H) relative to the OH group are well separated (if not in $CDCl_3$, then in C_6D_6 or after acetylation) both from each other and from other types of protons, thus allowing to determine the ratio of isomers. The same situation is often encountered for the olefinic proton if the double bond bears a substituent. The signals of 1-H have characteristic coupling patterns with 2-H and 7a-H. Those of the methyl groups at C-3 appear prominently in the aliphatic region; different intensities allow them to be grouped to pairs in most cases. Further information of this kind, as well as additional data for 2-H and 7a-H were obtained for **18b,e,f,h** through isolation or enrichment of individual isomers. 4-H and 5-H generally appear as ill-structured multiplets in the aliphatic region. The proximity of the signals, the presence of multiple and long-range couplings, and the additional difficulty to assign endo and exo protons render them quite useless for the present discussion.

The attempt to assign the stereochemistry of (if possible) all of the cyclization products **18** was made in two steps: (1) Establishment of four series of isomers through correlation of their NMR spectra (Table II). All of the characteristic protons mentioned above, and in most cases several of them at a time, could be used in appropriate cases. Agreement is best if the modified part of the molecule is far from the probe, e.g. Me and 6-H but not 2-H and 7a-H are suitable to compare **18b** and **18h**. Although the observed chemical shift ranges are mostly small,

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(9) (a) Smith, Z.; Carballo, N.; Wilson, E. B.; Marstokk, K.-M.; Møllendal, H. *J. Am. Chem. Soc.* **1985**, *107*, 1951. (b) Kahn, S. D.; Hehre, W. J. *Tetrahedron Lett.* **1985**, *26*, 3647.

Table II. Selected ^{1}H NMR Spectral Data of 2,3,3a,4,5,7a-Hexahydro-1*H*-inden-1-ols (18a–f and 18h)[a]

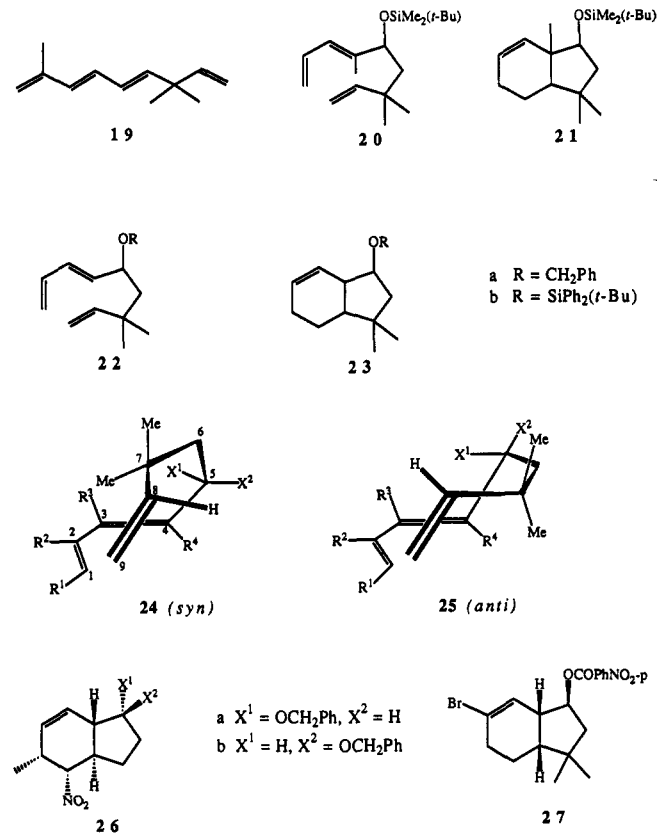
	δ(CH$_3$ at C-3)		δ(2-H)	
	δ(1-H)	δ(7a-H)	δ(7-H)	δ(6-H)
compd	$J_{1,2}$	$J_{1,7a}$	$J_{7,7a}$	$J_{3a,7a}$
18a	–		?	
	4.19, 4.27, 3.98, 3.83	?	?	?
	2.5/5, 1/5, 5/5, 5.5/9.5	5, 5, 5, 9.5	?	?
18b	1.00/1.05, 0.80/1.11, 0.96/1.17, 0.94/1.00		1.61/1.94, 1.58/1.92, 1.42/1.97, 1.41/2.05	
	4.26, 4.22, 4.02, 3.80	2.81, 2.18, 2.55, 2.18	5.67, 5.84, 5.92, 5.95	6.07, 5.77, 5.75, 5.63
	3.5/7, 1/6, 4/8.5, 6.5/9	6.5, 4, 7.5, 9.5	4.5, 1–2, 4, 1–2	6, ?, 7, 12
18c	0.99/1.04, 0.80/1.10, 0.95/1.16, 0.94/0.99		?, ?, 1.40/1.93, ?	
	4.19, 4.17, 3.98, 3.74	2.78, ?, 2.52, ?	5.33, 5.53, 5.60, 5.64	–
	?, 1/4, 4.5/7.5, 5.5/8	?, 4, 7.5, 8	?	?
18d	0.97*/1.05#, 0.81/1.07#, 0.95/1.18, 0.95*/1.02*#		?, ?, 1.42/1.93, ?	
	4.2, 4.2, 3.92, 3.82	2.80, ?, 2.55, ?	5.38, 5.62, 5.62, 5.69	–
	?, ?, 5.5/7, 7/10	?, ?, 8, 10	?	?
18e	1.00/1.04, 0.82/1.11, 0.97/1.17, 0.95/1.01		1.61/1.94, 1.59/1.95, 1.44/1.98, 1.42/2.06	
	4.29, 4.22, 4.09, 3.85	2.85, 2.26, 2.67, 2.26	6.03, 6.20, 6.26, 6.30	–
	4/7, 2/5.5, 4.5/8.5, 6.5/8.5	7, 4, 7, 8	5.5, 2, 4.5, 1–2	6.5, 11.5, 7, 11.5
18f	–, 0.82/1.11, 0.96/1.18, 0.95/0.99		–, ?/1.89, ?, 1.43/2.04	
	–, 4.31, 4.07, 4.00	–, ?, 2.45, ?	–	–, 5.45, 5.43, 5.26
	–, 1/4.5, 2.5/8.5, 6/9	–, 4.5, 6.5, 9	–	–, ?, 6.5, ?
18h	1.03/1.03, 0.81/1.07, 0.95/1.20, 0.95/0.98		1.68/1.77, 1.66/1.69, ?, 1.52/1.85	
	–	2.58, ?, 2.86, 2.49	5.65, 5.77*, 5.78, 5.87	6.06, 5.76*, 5.78, 5.62
	–	–	4.5, ?, ?, 1–2	5, ?, 7, 11

[a] Coupling constants in hertz. All values are given in the sequence cis-endo/trans-endo/cis-exo/trans-exo. Assignment of labeled values may be reversed.

the deviations within one stereochemical series are even smaller, provided that the just-mentioned precaution is observed and proper substituent corrections are made. In addition, pairs of data are compared in the case of the *gem*-dimethyl groups which for **18c,e,f,h** exhibit chemical shifts nearly identical with those of **18b**. The case of **18d** is somewhat ambiguous since pairing of the methyl resonances was not possible due to similar intensity of the signals (no isomer separation was attempted). The olefinic signals of **18c–f** and (7-H only) **18h** practically coincide with those of **18b** if substitution increments of –0.32 (**18c**), –0.27 (**18d**), +0.35 (**18e**), and –0.34 ppm (**18f**) are applied. Two of the 1-H signals consistently appear in close neighborhood at $\delta > 4.15$; they sometimes overlap (in $CDCl_3$) and (for **18a**) even change their sequence, but in all cases one of them has the appearance of a broadened triplet, one coupling being small (1–2 Hz) and unresolved, and the two others around 4–6 Hz. The 1-H signal at highest field consistently exhibits one medium and two large (8–10 Hz) couplings. Further correlations are observed for the 2-H signals of **18b,e** and (data available only for major isomers) **18c,d,f**. These observations permit assignment of all available isomers of **18a–f** and **18h** to four stereochemical series. (2) Identification of the relative stereochemistry for at least one member each of three of these series. Either directly or after appropriate decoupling, $J_{3a,7a}$ can be read for several compounds from the signal of 7a-H (for *trans-exo*-**18b** from that of 3a-H which appears at $\delta = 1.23$). Numerical accuracy is limited due to signal broadening by long-range couplings, but nevertheless all available values fall into two well-separated groups of 5–7 and 11–12 Hz, which are indicative of cis and trans ring junction. Independent confirmation comes from the coupling constant $J_{7,7a}$ which responds to the dihedral angle H(7)–C(7)–C(7a)–H(7a). Inspection of models shows that this dihedral angle is free to vary from approximately 0 to 90° in the cis, and from approximately 70 to 120° in the trans series, which precludes sizable coupling constants in the latter case. Indeed, all values found in the cis series are in the range 4–5.5 Hz, those in the trans series only 1–2 Hz.

The assignment of OH orientation relies on $J_{1,2}$ and $J_{1,7a}$. A molecular model shows that, in the case of trans ring junction, 1-H forms a large (approximately 160–170°) dihedral angle with 7a-H if OH is exo, and a small one (approximately 20–40°) if it is endo. $J_{1,7a}$ in the two trans series varies in the ranges of 4–6.5 Hz in one and 8–10 Hz in the other series, which can thus be recognized as endo and exo, respectively. The validity of this reasoning is corroborated by an X-ray analysis of **26a**[10] which has $J_{1,7a} = 5$ Hz; its C-1 epimer **26b** exhibits $J_{1,7a} = 9$ Hz. Further characteristics of the trans-endo series (with inclusion of literature compounds[10,11] are a small (0–2 Hz) and a me-

Scheme IV



(10) Kurth, M. J.; O'Brien, M. J.; Hope, H.; Yanuck, M. *J. Org. Chem.* 1985, *50*, 2626.

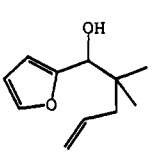
dium (4–6 Hz) value for $J_{1,2}$, whereas a medium (5.5–8 Hz) and a large (8–10 Hz) value are observed in the trans-exo series. The chemical shifts of 1-H are found for the former 0.31–0.44 ppm at lower field than for the latter.

Since *cis*-hexahydroindenes are considerably more flexible, $J_{1,2}$ and $J_{1,7a}$ are of little value here. In the two references which might provide examples,[10,11] only one cis isomer is formed in one case, and in the other case the ^{1}H NMR spectrum of the second isomer could be only partially analyzed; one author expressly states that his "... assignments... rest largely upon theoretical considerations". With one of the cis isomers being the major component of **18b**, the compound for which this work had originally been initiated, we felt that the question was worth an X-ray analysis and set out to prepare derivatives. Chromatographic isomer separation being tedious and inefficient, the derivative was to be preferentially prepared directly from the original mixture of isomers. Whereas the *p*-nitro- and *p*-bromobenzoates of **18b** proved unsuitable, the highly crystalline *p*-nitrobenzoate **27** of the major isomer of **18e** was obtained in pure form and satisfactory crystal quality after two recrystallizations. Its crystal structure (see the supplementary material) analysis revealed cis-exo stereochemistry. Saponification gave then pure *cis-exo*-**18e** which was used to assign the configuration of its series. A relation similar to that among the trans compounds is found for δ(1-H) of the endo- and exo-cis series: the former appears 0.20–0.33 ppm at lower field than the latter (including the only literature example,[11] the assignment of which is thereby corroborated).

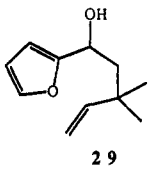
It remains to compare the experimental isomer ratios with the model predictions made earlier. For **18a–e**, a predominance of cis over trans products is indeed observed, the ratio varying only from 6:4 to 7:3. The cis-exo predominantes over the cis-endo isomer by factors between 3:1 and 6:1, which may reflect the reluctance of the OH group to occupy the more encumbered position on the developing concave face in the transition state. Among the trans isomers (which do not have concave/convex faces), endo and exo isomers are formed in equal amounts, or the former even slightly predominante. A brief investigation of the dependence of the isomer ratio on the reaction temperature and protective groups at oxygen was carried out in the case of **17b**. As expected, stereoselectivity drops with increasing temperature. O-Alkylation (to form **19a,b**) gives a slightly improved selectivity for the cis-exo product, and more exo than endo product among the trans isomers. A methyl group at C-3 (compound **17f**) changes the product ratio as expected. Only three compounds are formed, the doubly disfavored cis-endo isomer being absent (according to the above discussion, its olefinic proton should resonate at approximately δ = 5.73, around which position no signals are observed). The major product is *trans-exo*-**18f** arising from the transition state **25** with X^1 = H, X^2 = OH.

Nothing has to this point been said about **18g**, and the reason for this is the presence of the angular methyl group which interferes with all NMR criteria used above. No isomer ratio can be given in this case since the crude product is very impure, but it is apparent that one isomer strongly predominates, and this is the only one present after chromatography. The *tert*-butyldimethylsilyl ether **20** cyclizes more cleanly to give a mixture of two isomers of **21** in the ratio 78:22. The model predicts that these should be cis configurated, but we do not have evidence for or against this assignment. Finally, **17h** yields predominantly endo products in line with the predictions; trans isomers are slightly favored over cis.

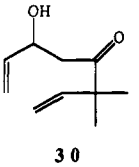
Attempted Diels–Alder Cyclization of Similar Substrates. If the diene moiety is part of a furan ring, Diels–Alder reactions may become reversible, and high temperatures required to activate recalcitrant starting materials commonly shift the equilibrium in their favor. Thus, only a trace of the cyclization product was obtained from **28**.[5b] We prepared the alcohol **29** from 2-lithiofuran[12] and 3,3-dimethyl-4-pentenal[13] as a furan analogue of **17b** and isomer of **28** and, not surprisingly, failed as well. No cyclization occurred at 185 °C whereas a complex mixture was formed at 230 °C (0.2 M in chlorobenzene).



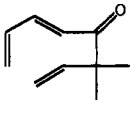
28



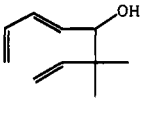
29



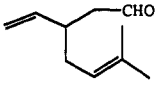
30



31



32



33

Another interesting variation of the present Diels–Alder substrates would be a reduction of the tether length so as to produce fused cyclobutanols. The scarcity of pertinent examples[1,14] may well result from a lack of attempts as from inherent difficulties. We synthesized therefore the requisite compound **32** along the same lines as above from acrolein and 3,3-dimethyl-4-penten-2-one[15] via intermediates **30** and **31**. Heating **32** to 190 °C did not furnish any Diels–Alder product, but mainly polymers; the only defined compound to be isolated was tentatively identified as the oxy-Cope product **33**. The availability of this alternative reaction pathway discouraged further work in this direction.

Experimental Section

NMR spectra (^{1}H, ^{13}C) were determined in $CDCl_3$ at 300 and 75 MHz, respectively. IR spectra were measured on neat samples except for **27** (Nujol suspension). Mass spectra were obtained in electron impact ionization mode at 70 eV. Melting points are uncorrected. Column chromatography was carried out with Merck silica gel 60 F_{254}, 0.063–0.2 mm. TLC was conducted on Merck silica gel 60 F_{254} plates. Starting materials **4a** and **5a,b,e** are commercially available. Compounds **4b**[3] and **5d**[16] were prepared

(11) Roush, W. R. *J. Am. Chem. Soc.* **1980**, *102*, 1390.

(12) Brandsma, L.; Verkruijsse, H. *Preparative Polar Organometallic Chemistry 1*; Springer: Berlin, 1987; p 127.

(13) (a) Cresson, P. *Bull. Soc. Chim. Fr.* **1964**, 2618. We extended the reaction period to 2 h at 210 °C to assure complete conversion. The reaction has also been performed at ordinary pressure under reflux for 24 h,[13b] conditions under which we found some starting material still to be present, which had to be removed by chromatography on SiO_2 (EtOAc/hexanes, 1:10; R_f = 0.72 (vinyl ether), 0.45 (aldehyde), 0.08 (3-methyl-2-buten-1-ol)). The last-mentioned compound was also present as an impurity since the preparation of the vinyl ether by its Hg^{2+}-catalyzed transetherification[13b,c] with ethyl vinyl ether proceeds only to an equilibrium, and the vinyl ether in our hands contained small amounts of the alcohol even after repeated fractionation. Since chromatography is therefore inevitable to obtain a pure product, it should be done on the vinyl ether stage where the extreme polarity difference of the components permits its efficient execution even on a large scale. (b) Boeckman, R. K.; Ko, S. S. *J. Am. Chem. Soc.* **1982**, *104*, 1033. (c) Watanabe, W. H.; Conlon, L. E. *Ibid.* **1957**, *79*, 2828.

(14) Al Holly, M. M.; Hobson, J. D. *Tetrahedron Lett.* **1970**, 3423.

(15) Déléris, G.; Pillot, J. P.; Rayez, J. C. *Tetrahedron* **1980**, *36*, 2215.

Table III. ^{1}H NMR Spectral Data for 6, 7 and 17[a]

compd	1c-H	1t-H	2-H	3-H	4-H	5-H	6-H	7-H or Me-7	8-H	9c-H	9t-H	OH	others
6a	5.29	5.14	5.86	4.58	2.70–2.61		2.56	2.34	5.80	5.05	4.99	3.00	
6b	5.28	5.12	5.84	4.54	2.63, 2.58		2.44	1.12	5.91	4.97	4.96	3.09	
6c	4.99[b]	4.85[b]		4.45	2.60 (m)		2.46	1.13	5.88	4.97	4.96	3.07	1.73
6d	5.62			4.63	2.65 (m)		2.46	1.12	5.91	4.97	4.95	3.09	*c*
6e	5.58	5.99		4.58	2.86, 2.73		2.46	1.13	5.91	4.99	4.98	3.36	
6f	5.22	5.04	5.87[b]		2.72, 2.56		2.41, 2.39	1.11	5.88[b]	4.96	4.97	4.21	1.26
6g (major)	5.29	5.17	5.77	4.42	2.63		2.53, 2.49	1.13	5.92	4.97	4.96	2.83	1.08
6g (minor)	5.27	5.17	5.83	4.17	2.57		*d*	1.13	5.94	4.96	4.94	*d*	1.05
7a[e]	5.66	5.54	6.46	7.14	6.19		2.68	2.38	5.84	5.03	4.98		
7b	5.65	5.53	6.44	7.10	6.17		2.54	1.13	5.91	4.95	4.93		
7c	5.40[b]	5.38[b]		7.16	6.13		2.57	1.14	5.92	4.95	4.94		1.88
7d	6.23			7.32	6.01		2.55	1.13	5.92	4.95	4.93		*f*
7e	5.99	6.20		7.04	6.50		2.57	1.14	5.92	4.94	4.95		
7f (*E*)	5.66	5.44	6.35		6.10		2.46	1.12	5.92	4.94	4.93		2.23
7f (*Z*)	5.61	5.44	7.68		6.04		2.44	1.12	5.92	4.94	4.93		1.98
7g	5.60	5.49	6.73	6.95			2.70	1.12	5.92	4.93	4.92		1.87
17a	5.22	5.10	6.33	6.23	5.72	4.18	*g*	2.15 (m)	5.83	5.04	4.98	*g*	
17b	5.20	5.08	6.30	6.20	5.68	4.28	1.63, 1.53	1.09, 1.07	5.93	5.01	5.00	1.78	
17c	4.96	4.96		6.27	5.64	4.30	1.66, 1.54	1.10, 1.07	5.93	5.01	5.00	1.78	1.83
17d	5.70			6.40	5.52	4.29	1.65, 1.53	1.09. 1.07	5.93	5.00	4.99	1.76	*h*
17e	5.61	5.79		6.23	6.06	4.50	1.63, 1.58	1.11, 1.08	5.94	5.04	5.03	1.71	
17f (*E*)	5.19	5.04	6.34		5.46	4.61	1.71, 1.47	1.09, 1.06	5.92	5.00	4.99	1.67	1.77
17f (*Z*)	5.26	5.16	6.74		5.37	4.73	1.69, 1.46	1.05	5.92	5.00	4.99	*d*	1.82
17g	5.19	5.09	6.56	6.04		4.14	1.60, 1.52	1.09, 1.07	5.92	5.01	5.00	1.78	1.74
17h	5.18	5.04	6.37	6.18	5.72		1.78, 1.67	1.09, 1.03	6.01	4.98	4.99		*i*

[a] Typical coupling constants. 6: $J_{2,3}$ = 5.5 Hz; $J_{3,4}$ = 3.5–4.5 Hz, 8–9.5 Hz; $J_{4,4}$ = 17–18.5 Hz. 7 and 17: $J_{2,3}$ = 10.5–11 Hz; $J_{3,4}$ = 15–16 Hz. 17: $J_{4,5}$ = 5.5–8.5 Hz; $J_{5,6}$ = 3.5–4 Hz, 8–8.5 Hz; $J_{6,6}$ = 14.5 Hz. $J_{1c,2}$, $J_{1t,2}$, $J_{8c,9}$, and $J_{8t,9}$ cannot be read by first-order rules because of too close proximity of the chemical shifts of 1c-H, 1t-H, and 8c-H, 8t-H. The apparent values are around 10.5 and 17 Hz for cis and trans couplings. [b] Assignments may be reversed. [c] 2.27 (m), 1.87 (m). [d] Hidden under signals of the major isomer. [e] $J_{6,7}$ = 7.5 Hz, $J_{7,8}$ = 6.5 Hz. [f] 2.47 (m), 1.98 (quint). [g] 6-H and OH form a multiplet at δ = 1.74–1.53. [h] 2.40 (t), 1.91 (quint). [i] 1.52–1.15 (m), 0.87 (t).

according to literature procedures.

5,5-Dimethyl-6-hepten-3-one (4c). To a suspension of 2.45 g (16 mmol) of pyridinium chlorochromate and 0.25 g (3 mmol) of sodium acetate in 15 mL of CH_2Cl_2 was added all at once a solution of 1.49 g (10.5 mmol) of **8** in 10 mL of CH_2Cl_2. The mixture was stirred for 2 h at room temperature in a water bath (to control the mildly exothermic reaction), then for another 2 h at 30–35 °C. Filtration over a short alumina column, evaporation, and bulb-to-bulb distillation at 55–60 °C (78 Torr) afforded 0.91 g (62%) of the ketone as a colorless liquid: ^{1}H NMR δ 5.92 (m, 1 H, 6-H), 4.95, 4.94 (each m, 1 H, 7-H), 2.40 (s, 2 H, 4-H), 2.39 (q, J = 7 Hz, 2 H, 2-H), 1.11 (s, 6 H, CH_3 at C-5), 1.00 (t, J = 7.5 Hz, 3 H, 1-H); IR ν 3085, 2965, 1715, 1640, 1362, 1109, 912 cm^{-1}; MS m/z (%) 140 (14), 111 (32), 83 (26), 69 (89), 57 (82), 41 (100); HRMS calcd for $C_9H_{16}O$ 140.1201, found 140.1201.

Cyclopentene-1-carboxaldehyde (5c). A solution of 10.1 mL (0.1 mol) of cyclohexene in 75 mL of methanol was ozonized with acetone/CO_2 cooling to a persistent blue color. The excess of ozone was removed by purging with argon, and 10.0 mL (0.136 mol) of dimethyl sufide was added dropwise at −78 °C. The mixture was thawed to 0 °C within 3 h and then stirred at 0 °C for 30 min and at room temperature (water bath) for 1 h. Volatiles were removed in vacuo, the residue was taken up in 200 mL of benzene, and 0.50 mL (5 mmol) of piperidine and 0.29 mL (5 mmol) of acetic acid were added. Refluxing under a Dean–Stark trap for 1.5 h produced an orange solution which, after cooling, was washed twice with 100 mL each of 2 N HCl (to remove most of the color), then with $NaHCO_3$ solution, and finally with brine; 100 mg of hydroquinone was added, and most of the benzene was distilled off over a 25-cm Vigreux column in a partial aspirator vacuum. The residue was distilled without a column to obtain 7.7 g of a colorless liquid [bp 57–60 °C (13 Torr)] which, according to the ^{1}H NMR spectrum, was a mixture of the known[17] **5c** and benzene in a ratio (by weight) of 82:18, corresponding to a corrected yield of **5c** of 6.3 g (65%). Removal of the benzene is unnecessary but could be achieved with some loss by fractionation. The ^{1}H NMR spectral data of **5c** agree with the literature values.[17c]

Aldol Addition of 4 and 5. General Procedure. To 1.2 equiv of diisopropylamine as a 0.4 M solution in THF was added dropwise from a syringe with dry ice cooling 1.1 equiv of *n*-butyllithium in hexanes. The solution was stirred at 0 °C for 30 min and recooled to −78 °C, and the ketone **4** in a small volume of THF was added dropwise within 5–20 min (depending on the reaction scale). After 1 h at −78 °C, the electrophilic component **5** diluted with a small volume of THF was added within a few min. The mixture was stirred for 20 min in the cold bath, which was removed before quenching with aqueous NH_4Cl. After thawing, the phases were separated, the aqueous phase was extracted with ether, and the combined organic phases were dried over $MgSO_4$ and evaporated. The crude product was chromatographed on SiO_2 using appropriate ethyl acetate/hexanes mixtures for elution, to remove polymers and small amounts of byproducts. In most cases, distillation yielded the aldols **6** as colorless oils; **6e** was used in the next step without distillation. ^{1}H NMR: Table III. ^{13}C NMR: Table IV.

3-Hydroxy-1,8-nonadien-5-one (6a) was prepared on a 25-mmolar scale in 78% yield. EtOAc/hexanes, 1:1, was used for chromatography; the SiO_2 was deactivated with 5% of methanol prior to use. **6a** was obtained after bulb-to-bulb distillation [75–80 °C (1.4 Torr)] as an inseparable mixture with its regioisomer, 4-acetyl-1,6-heptadien-3-ol (**9**), of which the following ^{1}H NMR signals were discernible: δ 5.21 (m, 1 H), 4.38, 4.25 (each br q, J = 4.5 and 6 Hz, resp, 1 H, 3-H; 2 diastereoisomers in the ratio 4:1), 2.82–2.72 (m, 1 H, 4-H), 2.19 (s, 3 H, CH_3); IR ν 3438, 3081, 1709, 1642, 995, 920 cm^{-1}; MS m/z (%) 136 (3), 83 (40), 55 (62), 43 (100); HRMS calcd for $C_9H_{12}O$ (M − H_2O) 136.0888, found 136.0888.

3-Hydroxy-7,7-dimethyl-1,8-nonadien-5-one (6b) was prepared on a 100 mmolar scale in 86% yield. EtOAc/hexanes, 2:5, was used for chromatography. Oven temperature 65 °C/0.15 torr. IR ν 3434, 3085, 2963, 1707, 1640, 995, 920 cm^{-1}. MS m/z (%) 182 (2), 111 (42), 83 (37), 69 (82), 57 (69), 43 (100). Anal. Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95. Found: C, 72.26; H, 9.80.

3-Hydroxy-2,7,7-trimethyl-1,8-nonadien-5-one (6c) was prepared on a 50-mmolar scale in 64% yield. EtOAc/hexanes, 1:5, was used for chromatography: oven temperature 70–75 °C (0.45 Torr); IR ν 3443, 3083, 2963, 1705, 1653, 907 cm^{-1}; MS m/z (%) 196 (0.5), 178 (1), 111 (24), 83 (27), 71 (51), 69 (100); HRMS

(16) Smith, A. B., III; Levenberg, P. A.; Jerris, P. J.; Scarborough, R. M., Jr.; Wovkulich, P. M. *J. Am. Chem. Soc.* **1981**, *103*, 1501.

(17) (a) Baeyer, A.; von Liebig, H. *Ber. Dtsch. Chem. Ges.* **1898**, *31*, 2107. (b) Henbest, H. B.; Jones, E. R. H. *J. Chem. Soc.* **1950**, 3628. (c) Fleet, G. W.; Harding, P. J. C. *Tetrahedron Lett.* **1979**, 975.

Table IV. ^{13}C NMR Spectral Data for 6, 7, and 17 [Chemical Shifts Relative to $CDCl_3$ = 77.1; in brackets: $^1J_{C,H}$ (Hz; s = singlet)]

compd	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	Me-7	others
6a	114.6 (157)[a]	139.2 (154)	68.4 (144)	48.4 (126)	209.8	42.4	27.2	136.6	115.1[a]		
6b	114.7 (158)	139.1 (154)	68.4 (145)	50.7 (126)	210.1	54.8	36.4	146.8	111.0	27.0, 26.8	
6c	111.0[a]	145.7 (s)	70.9 (141)	49.5 (126)	210.5	54.9	36.4	146.8	110.9[a]	27.1, 26.8	18.2
6d	125.2 (160)	145.1 (s)	66.7 (143)	49.6 (126)	210.4	54.7	36.2	146.7	110.8	26.9, 26.7	*d*
6e	116.9 (163)	134.6 (s)	71.4 (149)	49.1 (127)	209.0	54.8	36.3	146.6	111.0	27.0, 26.7	
6f	111.6 (156)[a]	143.5 (153)	71.4 (s)	53.4[b]	210.6	55.0[b]	35.9	146.3	110.5[a]	27.6[c]	26.5[c]
6g (major)	115.5 (157)	137.8 (153)	72.4 (145)	51.3 (128)	213.9	53.4	36.1	146.8	110.6	26.9, 26.7	10.4
6g (minor)	116.3 (156)	138.4 (154)	75.1 (145)	51.6 (131)	213.9	54.2	36.1	147.0	110.4	26.7	13.2
7a	126.3 (160)	135.2	142.5 (154)	130.3 (157)	199.7	39.6	28.0	137.1	115.2		
7b	126.2 (158)	135.2 (156)	142.0 (154)	131.5 (157)	199.4	52.4	36.7	147.1	110.6	27.0	
7c	125.1	140.9	144.6	128.1	199.7	52.6	36.8	147.4	110.7	27.1	18.1
7d	138.6[a]	141.9[a]	141.8[a]	128.0	200.0	52.3	36.8	147.5	110.6	27.2	*e*
7e	127.6 (166)	129.0 (s)	138.7 (159)	132.9 (160)	197.9	53.4	36.5	146.6	110.7	26.8	
7f (*E*)	128.4 (154)	140.5 (155)	149.1 (s)	120.1 (158)	200.6	55.9	36.8	147.1	110.4	26.9	13.1[f]
7f (*Z*)	127.0 (153)	134.6 (160)	147.7 (s)	121.1 (156)	199.9	55.7	36.8	147.1	110.4	26.9	20.1[f]
7g	124.0 (159)	137.6 (155)	132.6 (157)	137.6 (s)	200.3	47.6	36.3	147.2	110.0	26.9	11.4
17a	117.3 (154)	136.3[a]	138.1[a]	130.9 (152)	71.6	36.1	29.5	136.4[a]	114.7		
17b	117.2 (157)	136.5 (153)[a]	137.5 (152)[a]	130.0 (155)	70.0	49.8	36.3	148.6	111.1	28.4, 26.3	
17c	116.5 (157)	141.4 (s)	133.3 (153)[a]	132.1 (153)[a]	70.4	50.0	36.3	148.7	111.1	28.4, 26.3	18.8
17d	126.5 (151)	142.1 (s)	133.4 (153)[a]	131.0[a]	70.7	50.2	36.4	148.8	111.1	28.6, 26.2	*g*
17e	119.6 (166)	129.5 (s)	140.6 (157)	127.1 (159)	69.0	49.8	36.3	148.4	111.3	28.2, 26.2	
17f (*E*)	112.9 (157)	141.0 (153)	133.0 (s)[f]	135.6 (153)	66.4	50.2	36.3	148.6	111.0	28.5, 26.2	12.2[f]
17f (*Z*)	115.3 (158)	133.9[a]	134.0 (s)[f]	133.3[a]	65.3	50.3	36.3	148.7	111.0	28.5, 26.2	19.7[f]
17g	116.6 (157)	132.6 (152)	125.0 (151)	141.2 (s)	74.4	47.6	36.1	148.2	110.7	27.4, 26.6	12.2
17h	115.8 (157)	136.7 (152)	141.6 (150)	127.6 (154)	76.0	53.4	37.1	149.3	111.2	26.9, 25.3	*h*

[a-c] These assignments may be reversed. No attempt was made to corroborate assignments by C–H correlated spectra. [d] 32.0, 31.5, 23.0. [e] 33.7, 30.8, 23.1. [f] *E* and *Z* isomers not assigned. [g] 32.9, 31.8, 23.2. [h] 43.8, 25.3, 23.1, 14.1.

calcd for $C_{12}H_{18}O$ (M – H_2O) 178.1358, found 178.1357.

1-(1-Cyclopentenyl)-1-hydroxy-5,5-dimethyl-6-hepten-3-one (6d) was prepared on a 10-mmolar scale in 90% yield. EtOAc/hexanes, 1:5, was used for chromatography: oven temperature 75 °C (0.5 Torr); IR ν 3428, 3083, 2957, 1707, 1640, 914 cm^{-1}; MS *m/z* (%) 222 (2), 111 (40), 83 (34), 69 (100); HRMS calcd for $C_{14}H_{22}O_2$ 222.1620, found 222.1620.

2-Bromo-3-hydroxy-7,7-dimethyl-1,8-nonadien-5-one (6e) was prepared on an 18-mmolar scale in 82% yield. EtOAc/hexanes, 1:5, was used for chromatography. The compound could not be distilled: IR ν 3438, 3088, 2963, 1706, 1636, 912 cm^{-1}; MS *m/z* (%) 263, 261, (0.1, 0.1), 181 (50), 137, 135 (54, 56), 111 (31), 83 (37), 69 (90); HRMS calcd for $C_{11}H_{17}O_2$ (M – Br) 181.1229, found 181.1229.

3-Hydroxy-3,7,7-trimethyl-1,8-nonadien-5-one (6f) was prepared on a 10-mmolar scale in 53% yield. EtOAc/hexanes, 1:8, then 1:5 was used for chromatography: IR ν 3478, 3085, 2967, 1700, 1640, 920 cm^{-1}; MS *m/z* (%) 196 (0.2), 111 (19), 83 (15), 71 (91), 69 (100). Anal. Calcd for $C_{12}H_{20}O_2$: C, 73.43; H, 10.27. Found: C, 73.06; H, 10.46.

3-Hydroxy-4,7,7-trimethyl-1,8-nonadien-5-one (6g) was prepared on a 2-mmolar scale in 90% yield. EtOAc/hexanes, 2:5, was used for chromatography: oven temperature 55 °C (0.85 Torr). The product is a 3:1 mixture of two diastereoisomers: IR ν 3453, 3083, 2965, 1705, 1638, 920 cm^{-1}; MS *m/z* (%) 196 (0.3), 181 (2), 110 (23), 97 (51), 74 (50), 69 (100); HRMS calcd for $C_{11}H_{17}O_2$ (M – CH_3) 181.1229, found 181.1229.

Dehydration of Aldols 6 to Dienones 7. For each method A–D a representative example is given below. EtOAc/hexanes, 1:10, was used for column chromatography unless specified otherwise. ^1H NMR: Table III. ^{13}C NMR: Table IV.

1,3,8-Nonatrien-5-one (7a) by Method C. To 1.54 g (10 mmol) of **6a** and 3.5 mL (25 mmol) of triethylamine in 20 mL of CH_2Cl_2 was added at –78 °C within 25 min 1.68 mL (10 mmol) of trifluoromethanesulfonic anhydride in 10 mL of CH_2Cl_2. Stirring at –78 °C was continued for 15 min, 50 mL of saturated aqueous $NaHCO_3$ was added, and the mixture was stirred for another 15 min at room temperature. Washing with 50 mL of 10% $KHSO_4$ solution was followed by $MgSO_4$ drying and evaporation. The residue was chromatographed on SiO_2 with EtOAc/hexanes, 1:2. The eluate, on concentration and bulb-to-bulb distillation, yielded 0.58 g (43%) of **7a**: oven temperature 65–70 °C (26 Torr); IR ν 1690, 1663, 1622, 1592, 1007, 918 cm^{-1}.

7,7-Dimethyl-1,3,8-nonatrien-5-one (7b). By Method A. A solution of 20.0 g (110 mmol) of **6b**, 0.9 mL (11 mmol) of pyridine, and 2.1 g (11 mmol) of *p*-toluenesulfonic acid monohydrate in 330 mL of benzene was heated to boiling. The vapors were passed through the pressure equalizer of a dropping funnel and condensed, and the distillate was passed through 50 g of activity grade 1 alumina contained in the dropping funnel (to adsorb water), from where it was returned into the reaction flask. After 5.5 h, the alumina was replaced by a fresh filling, and water separation was continued for 3.5 h. The solution was then cooled, washed successively with 2 × 50 mL of saturated $KHSO_4$ solution, 100 mL of water, and 50 mL of saturated $NaHCO_3$ solution, evaporated, and chromatographed on SiO_2. The product **7b** was eluted with EtOAc/hexanes, 1:10, unreacted **9b** with EtOAc/hexanes, 2:5. Bulb-to-bulb distillation of the respective fractions yielded 12.2 g (68%) of **7b**, oven temperature 45–50 °C (0.15 Torr), and 1.7 g (8%) of starting material. **By Method B:** To 0.62 g (3.4 mmol) of **6b** and 1.4 mL (10 mmol) of triethylamine in 16.5 mL of CH_2Cl_2 was added dropwise with ice cooling 0.31 g (4 mmol) of methanesulfonyl chloride. The mixture was stirred at 0 °C for 1.5 h and then at room temperature for 2 h. Aqueous workup (NH_4Cl/CH_2Cl_2), drying over $MgSO_4$, and column chromatography on SiO_2 yielded 0.47 g (85%) of **7b** which was of good purity without distillation: IR ν 1682, 1653, 1619, 1590, 1009, 916 cm^{-1}; MS *m/z* (%) 164 (7), 149 (12), 96 (60), 81 (76), 69 (58), 41 (100). Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.97. Found: C, 79.99; H, 9.82.

2,7,7-Trimethyl-1,3,8-nonatrien-5-one (7c) was prepared by method B on a 37-mmolar scale in 75% yield: bp 62–66 °C (0.45 Torr); IR ν 1682, 1653, 1615, 1593, 984, 911 cm^{-1}; MS *m/z* (%) 178 (8), 163 (12), 110 (38), 95 (100), 69 (42), 67 (70); HRMS calcd for $C_{12}H_{18}O$ 178.1358, found 178.1357.

1-(1-Cyclopentenyl)-5,5-dimethyl-1,6-heptadien-3-one (7d) was prepared by method B on an 8-mmolar scale in 81% yield: oven temperature 75 °C (0.8 Torr); IR ν 1680, 1653, 1610, 1586, 981, 912 cm^{-1}; MS *m/z* (%) 204 (15), 189 (4), 136 (19), 135 (24), 121 (100), 69 (27); HRMS calcd for $C_{14}H_{20}O$ 204.1514, found 204.1515.

2-Bromo-7,7-dimethyl-1,3,8-nonatrien-5-one (7e) was prepared by method B. The increased lability of this compound required a modification of the workup procedure as follows: After the aqueous workup and drying over $MgSO_4$, the solution was chromatographed on SiO_2 with benzene/ether, 1:1 (it may be concentrated before application on the column, *but not completely*). The eluate was concentrated to ca. 0.3 M, and this

solution was used in the next step. A 6-mmolar run gave, after evaporation, an 84% yield of **7e**, but the neat liquid product suffered darkening and a viscosity increase within minutes, and the ^1H NMR spectrum exhibited broad polymer signals besides those listed in Table II: IR (immediately after evaporation) ν 1686, 1607, 1582, 1364, 967, 912 cm^{-1}; MS (from a dilute solution) m/z (%) 244, 242, (0.5, 0.5), 229, 227 (2, 2), 163 (21), 161, 159 (46, 50), 133, 131 (17, 17), 69 (100); HRMS calcd for $C_{10}H_{12}{}^{79}BrO$ (M - CH_3) 227.0071, found 227.0071.

3,7,7-Trimethyl-1,3,8-nonatrien-5-one (7f) was prepared by method A on a 1-mmolar scale in 67% yield. Oven temperature 55–60 °C (1 Torr). The product is an ca. 2:1 mixture of *E* and *Z* isomers: IR ν 1674, 1582, 1094, 914, 733 cm^{-1}; MS m/z (%) 178 (5), 163 (2), 95 (100), 69 (37). HRMS calcd for $C_{12}H_{18}O$ 178.1358, found 178.1358.

4,7,7-Trimethyl-1,3,8-nonatrien-5-one (7g) by Method D. To 290 mg (1.48 mmol) of **6g** and 0.42 mL (3.0 mmol) of triethylamine in 3 mL of CH_2Cl_2 was added dropwise at 0 °C 0.14 mL (1.8 mmol) of methanesulfonyl chloride. After 20 min at room temperature, water was added. The phases were separated, the aqueous phase was extracted with more CH_2Cl_2, and the combined organic phases were washed with 10% $KHSO_4$ and saturated $NaHCO_3$ solutions, dried over $MgSO_4$, and evaporated to obtain 405 mg (100%) of crude **3-[(methylsulfonyl)oxy]-4,7,7-trimethyl-1,8-nonadien-5-one (11)**, which was used in this form in the following step. Pure **11** could be isolated with serious losses due to decomposition by column chromatography (SiO_2, EtOAc/hexanes, 1:3) as a colorless oil: ^1H NMR (major isomer) δ 5.90 (m, 1 H, 8-H), 5.88 (m, 1 H, 2-H), 5.43 (m, 1 H, 1c-H), 5.37 (m, 1 H, 1t-H), 5.18 (t, J = 7 Hz, 3-H), 4.95 (m, 1 H, 9c-H), 4.94 (m, 1 H, 9t-H), 2.99 (s, 3 H, SO_2CH_3), 2.88 (quint, J = 7 Hz, 1 H, 4-H), 2.52, 2.49 (AB q, J = 15.5 Hz, 2 H, 6-H), 1.16 (d, J = 7 Hz, 3 H, CH_3 at C-4), 1.11 (s, 6 H, CH_3 at C-7); (minor isomer) δ 5.93 (m, 1 H, 8-H), 5.82 (m, 1 H, 2-H), 5.47 (m, 1 H, 1c-H), 5.42 (m, 1 H, 1t-H), 5.12 (t, 1 H, 3-H), 4.97 (m, 1 H, 9c-H), 4.95 (m, 1 H, 9t-H), 2.94 (s, 3 H, SO_2CH_3), 2.87 (m, overlapping, 1 H, 4-H), 2.65, 2.63 (AB q, 2 H, 6-H), 1.14 (s, 6 H, CH_3 at C-7), 1.01 (d, J = 7 Hz, CH_3 at C-4); IR ν 2965, 1715, 1640, 1360, 1177, 928 cm^{-1}; MS m/z (%) 274 (0.4), 111 (18), 95 (10), 69 (64), 68 (100); HRMS calcd for $C_{13}H_{22}O_4S$ 274.1239, found 274.1238. To 405 mg (1.48 mmol) of **11** in 8 mL of THF was added dropwise at 0 °C 0.45 mL (3.0 mmol) of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU). After 15 min each at 0 °C and room temperature, the mixture was worked up according to the General Procedure, and the crude product was chromatographed on SiO_2 and evaporated to obtain 195 mg (74%) of **7g** in good purity. Method A furnished only a 32% yield after bulb-to-bulb distillation on a 2-mmolar scale: oven temperature 50 °C (1.1 Torr); IR ν 3085, 2963, 1671, 1653, 988, 916 cm^{-1}; MS m/z (%) 178 (8), 163 (6), 110 (19), 95 (100), 69 (65); HRMS calcd for $C_{12}H_{18}O$ 178.1358, found 178.1357.

5,5-Dimethyl-6-hepten-3-ol (8). A solution of 1.35 g (12 mmol) of 3,3-dimethyl-4-pentenal[13] in 10 mL of ether was added dropwise at −20 °C within 15 min to a solution of EtMgBr prepared from 0.44 g (18 mmol) of Mg and 1.12 mL (15 mmol) of ethyl bromide in 13 mL of ether. The mixture was stirred in the cold bath for another 15 min and then hydrolyzed with 15 mL of saturated aqueous NH_4Cl solution. Suction filtration, aqueous workup (ether; $MgSO_4$), and filtration with ether over a short column of silica gel yielded the crude product which was bulb-to-bulb distilled at 50 °C (13 Torr) to obtain 1.53 g (90%) of **8** as a colorless liquid: ^1H NMR δ 5.93 (m, 1 H, 6-H), 5.03, 5.00 (each m, 1 H, 7-H), 3.64 (m, 1 H, 3-H), 1.77 (br s, 1 H, OH), 1.55–1.37 (m, 4 H, 2,4-H), 1.08, 1.05 (each s, 3 H, CH_3 at C-5), 0.91 (t, J = 7.5 Hz, 3 H, 1-H); IR ν 3380, 3083, 2961, 2926, 1638, 911 cm^{-1}; MS m/z (%) 142 (1), 124 (7), 109 (18), 95 (63), 85 (55), 69 (100); HRMS calcd for $C_9H_{18}O$ 124.1252, found 124.1252.

Reduction of 1,3,8-Nonatrien-5-ones (7). General Procedure. A 0.17 M solution/suspension of $LiAlH_4$ (0.5 equiv relative to **10**) in ether was cooled in a CCl_4/CO_2 bath, and a 0.5 M ethereal solution of **7** (or the crude benzene solution in the case of **7e**) was added dropwise. The reaction was monitored by TLC; it was usually instantaneous. In the case of **7e,f** it was necessary to stir for 30 min at 0 °C. After completion of the reaction, the mixture was hydrolyzed with saturated Na_2SO_4 solution (0.5 mL per mmol of $LiAlH_4$), anhydrous Na_2SO_4 was added to bind free water, and the whole was poured on a short SiO_2 column and eluted with an appropriate EtOAc/hexanes mixture. The products obtained on evaporation were pure enough for the subsequent Diels–Alder reactions; some of them could be further purified by bulb-to-bulb distillation. ^1H NMR: Table III. ^{13}C NMR: Table IV.

1,3,8-Nonatrien-5-ol (17a) was prepared on a 9-mmolar scale in 98% yield: oven temperature 55 °C (4 Torr); IR ν 3353, 3083, 1642, 1605, 1003, 909 cm^{-1}; MS m/z (%) 138 (1.5), 120 (6), 83 (100), 55 (93); HRMS calcd for C_9H_{12} (M - H_2O) 120.0939, found 120.0939.

7,7-Dimethyl-1,3,8-nonatrien-5-ol (17b) was prepared on a 100-mmolar scale in 98% yield: oven temperature 50–60 °C (0.65 torr); IR ν 3374, 1638, 1605, 1003, 908 cm^{-1}; MS m/z (%) 151 (13), 148 (3), 133 (6), 83 (92), 69 (100), 55 (75); HRMS calcd for $C_{10}H_{15}O$ (M - CH_3) 151.1123, found 151.1123.

2,7,7-Trimethyl-1,3,8-nonatrien-5-ol (17c) was prepared on a 26-mmolar scale in 98% yield: oven temperature 60 °C (0.45 torr); IR ν 3364, 1636, 1609, 967, 911, 887 cm^{-1}; MS m/z (%) 180 (1), 162 (6), 97 (50), 69 (79), 41 (100); HRMS calcd for $C_{12}H_{18}$ (M - H_2O) 162.1408, found 162.1409.

1-(1-Cyclopentenyl)-5,5-dimethyl-1,6-heptadien-3-ol (17d) was prepared on a 6-mmolar scale in 92% yield. Attempted distillation resulted in decomposition: IR ν 3368, 1638, 965, 911 cm^{-1}; MS m/z (%) 206 (6), 191 (4), 188 (3), 173 (5), 69 (21), 44 (100); HRMS calcd for $C_{14}H_{22}O$ 206.1307, found 206.1306.

2-Bromo-7,7-dimethyl-1,3,8-nonatrien-5-ol (17e) was prepared from crude **7e** on a 2-mmolar scale in an overall yield of 68% (from **6e**). It is not distillable and quite sensitive to polymerization and should be used in the next step without delay: IR (immediately after evaporation) ν 3395, 1636, 1588, 957, 914 cm^{-1}; MS (from a dilute solution) m/z (%) 246, 244 (0.5, 0.5), 228, 225 (3.5, 3.5), 165 (70), 163, 161 (52, 56), 147 (55), 43 (100), 41 (100); HRMS calcd for $C_{11}H_{15}{}^{79}Br$ (M - H_2O) 226.0357, found 226.0357.

3,7,7-Trimethyl-1,3,8-nonatrien-5-ol (17f) was prepared on a 0.5-mmolar scale in 89% yield. The product is an ca. 3:1 mixture of *E* and *Z* isomers: oven temperature 55–60 °C (0.55 Torr); IR ν 3364, 1640, 1607, 990, 909 cm^{-1}; MS m/z (%) 180 (0.5), 165 (5), 162 (3), 147 (5), 97 (100), 69 (94); HRMS calcd for $C_{11}H_{17}O$ (M - CH_3) 165.1279, found 165.1279.

4,7,7-Trimethyl-1,3,8-nonatrien-5-ol (17g) was prepared on a 1-mmolar scale in 95% yield: oven temperature 70 °C (0.9 Torr); IR ν 3389, 1638, 1599, 988, 905 cm^{-1}; MS m/z (%) 165 (1), 69 (100); HRMS calcd for $C_{11}H_{17}O$ (M - CH_3) 165.1279, found 165.1279.

5-Butyl-7,7-dimethyl-1,3,8-nonatrien-5-ol (17h). A solution of 0.71 mL (1.1 mmol) of *n*-butyllithium (1.55 M in hexanes) was added dropwise from a syringe to 164 mg (1 mmol) of **10b** in 5 mL of ether at −78 °C. After 5 min, 0.2 mL of water was added, and the mixture was thawed and dried over $MgSO_4$. Evaporation yielded 226 mg (102%) of **17h**, which was satisfactory for the Diels–Alder cyclization, but contained ca. 10% of the 1,4-addition product **12**. A pure sample of **17h** was obtained by column chromatography on SiO_2 with EtOAc/hexanes, 1:20: IR ν 3565, 1638, 1605, 1007, 901 cm^{-1}; MS m/z (%) 222 (1), 204 (5), 139 (33), 81 (61), 69 (92), 41 (100); HRMS calcd for $C_{15}H_{24}$ (M - H_2O) 204.1878, found 204.1878.

The forerun yielded a small quantity of **3,3-dimethyl-7-vinyl-1-undecen-5-one (12)**; it could as well be isolated from the forerun of **18h** (see there) if crude **17h** was cyclized directly: ^1H NMR δ 5.91 (m, 1 H, 2-H), 5.78 (m, 1 H, 1′-H of vinyl at C-7), 5.02–4.90 (m, 4 H, remaining olefinic H), 2.53 (m, 1 H, 7-H), 2.43–2.35 (m, 4 H, 4,6-H), 1.40–1.15 (m, 6 H, 8,9,10-H), 1.11 (s, 6 H, CH_3 at C-3), 0.87 (t, J = 7.5 Hz, 3 H, 11-H).

Autoxidation of 7c. A 75-mg sample of **10c** was kept in a 40-mL vial under an ordinary atmosphere at 0–5 °C in the dark for 3.5 weeks, after which time the following spectra of the major product, **8,9-epoxy-3,3,8-trimethylnona-1,6-dien-5-one (13)**, were recorded: ^1H NMR δ 6.73 (br d, J = 16 Hz, 1 H, 7-H), 6.22 (d, J = 16.5 Hz, 1 H, 6-H), 5.91 (m, 1 H, 2-H), 4.94 (m, 1 H, 1c-H), 4.92 (m, 1 H, 1t-H), 4.12 (s, 1 H, 9-H), 2.56 (s, 2 H, 4-H), 1.36 (s, 3 H, CH_3 at C-8), 1.10 (s, 6 H, CH_3 at C-3); ^{13}C NMR δ 198.8 (C-5), 147.2, 144.4 (C-6,7), 130.5 (C-2), 110.9 (C-1), 83.5 (C-9), 77.5 (C-8), 52.6 (C-4), 36.7 (C-3), 27.2 (CH_3 at C-7), 20.7 (CH_3 at C-3). This compound decomposed on chromatography on SiO_2 (EtOAc/hexanes 1:15). After several unidentified byproducts, 1.3 mg (2%) of **7,7-dimethyl-3,8-nonadiene-2,5-dione (15)** was eluted (R_f = 0.10): ^1H NMR δ 6.81, 6.76 (AB q, J = 16.5 Hz, 2 H, 3,4-H), 5.90

(m, 1 H, 8-H), 4.97 (m, 1 H, 9t-H), 4.96 (m, 1 H, 9c-H), 2.64 (s, 2 H, 6-H), 2.36 (s, 3 H, 1-H), 1.14 (s, 6 H, CH_3 at C-7); IR ν 2926, 1684, 1362, 1075, 912 cm^{-1}; MS m/z (%) 180 (4), 149 (11), 137 (7), 69 (34), 55 (85), 43 (100); HRMS calcd for $C_{11}H_{16}O_2$ 180.1150, found 180.1151.

Autoxidation of 7d. A 29-mg sample of **7d** was kept in a 10-mL vial under an ordinary atmosphere at 0–5 °C in the dark for 4 weeks, after which time ^1H and ^{13}C NMR indicated the presence, besides some starting material, of a major product, **3,3-dimethyl-7-(6′-oxabicyclo[3.1.0]hex-1′-yl)hepta-1,6-dien-5-one (14).** This compound is more stable than the analogous product **13**, and part of it (7 mg, 22%) could be isolated, after a forerun of **7d**, by column chromatography (SiO_2, EtOAc/hexanes, 1:5, R_f = 0.47). Further elution with EtOAc/hexanes, 2:5, yielded 5.5 mg of very impure **10,10-dimethyl-5,8-dioxo-6,11-dodecadienal (16)**, which was further purified by HPLC (SiO_2, EtOAc/hexanes, 15:85). Compound **14**: ^1H NMR δ 6.72, 6.35 (AB q, J = 16 Hz, 2 H, 6,7-H), 5.90 (m, 1 H, 2-H), 4.95 (m, 1 H, 1c-H), 4.94 (m, 1 H, 1t-H), 3.47 (s, 1 H, 5′-H), 2.53 (s, 2 H, 4-H), 2.12–1.45 (m, 6 H, 2′,3′,4′-H), 1.12 (s, 6 H, CH_3); ^{13}C NMR δ 147.2 (d), 142.5 (d, J = 156 Hz, C-6,7), 131.6 (d, J = 157 Hz, C-2), 110.9 (t, J = 156 Hz, C-1), 66.6 (d, J = 183 Hz, C-5′), 52.4 (t, J = 127 Hz, C-4), 36.8 (s, C-3), 28.2 (t), 27.8 (t), 27.2 (2 q, CH_3), 19.3 (t, J = 133 Hz). C-5 and C-1′ were not observed; IR ν 1690, 1661, 1626, 978, 928, 914 cm^{-1}. Compound **16**: ^1H NMR δ 9.78 (s, 1 H, 1-H), 6.86, 6.78 (AB q, J = 16 Hz, 2 H, 6,7-H), 5.90 (m, 1 H, 11-H), 4.97 (m, 1 H, 12t-H), 4.96 (m, 1 H, 12c-H), 2.71 (t, J = 7 Hz, 2 H, 4-H), 2.63 (s, 2 H, 9-H), 2.54 (dt, J = 7 Hz (t), 1 Hz (d), 2 H, 2-H), 1.97 (quint, J = 7 Hz, 2 H, 3-H), 1.14 (s, 6 H, CH_3); ^{13}C NMR δ 146.6, 137.6, 135.6, 111.5, 53.3, 42.8, 40.4, 27.1, 16.0, the signals of 4 carbon atoms were not observed; IR ν 2726, 1725, 1682, 982, 916 cm^{-1}; MS m/z (%) 236 (2.5), 221 (3), 137 (35), 97 (24), 83 (20), 69 (100); HRMS calcd for $C_{14}H_{20}O_3$ 236.1412, found 236.1412.

Intramolecular Diels–Alder Reactions of 17. General Procedure. A chlorobenzene (**17a**, toluene; **17g**, tetralin) solution 0.2 M in **17** and 2 mM in tributylamine was purged with argon and heated in a screw-capped Pyrex vial (for small scale runs) or pressure bottle, which had previously been washed with aqueous NaOH solution, to the temperatures and for the periods of time indicated in Table I. After distillation of the solvent in vacuo, the residue was chromatographed on SiO_2 using appropriate EtOAc/hexanes mixtures for elution, and the eluate was concentrated and distilled to obtain **18** as colorless liquids or in some cases crystals. ^1H NMR: Table II.

2,3,3a,4,5,7a-Hexahydro-1*H*-inden-1-ol (18a): oven temperature 80–85 °C (25 torr); IR ν 3349, 3019, 2921 cm^{-1}; MS m/z (%) 138 (7), 120 (78), 92 (50), 91 (79), 79 (100); HRMS calcd for $C_9H_{14}O$ 138.1045, found 138.1045.

2,3,3a,4,5,7a-Hexahydro-3,3-dimethyl-1*H*-inden-1-ol (18b): bp 85.5–88.5 °C (0.8 Torr); IR ν 3353, 3021, 2926, 1366, 1057, 704 cm^{-1}; MS m/z (%) 166 (4), 107 (66), 92 (63), 85 (71), 79 (100). Anal. Calcd for $C_{11}H_{18}O$: C, 79.46; H, 10.91. Found: C, 79.68; H, 11.25.

Isomer separation or enrichment was effected by chromatographing 200 mg of the mixture on SiO_2 (50 × 2.5 cm, EtOAc/hexanes, 1:5); R_f = 0.46–0.21 (no individual spots because of tailing; judgement of purity by ^1H NMR). The order of polarity is cis-endo < cis-exo ≤ trans-endo < trans-exo. NMR in addition to Table II, *cis-endo*-**18b**: ^1H NMR δ 2.13 (m, 1 H), 1.98 (m, 1 H), 1.70 (m, 1 H), ca. 1.60 (m, 1 H), 1.41 (dq, J = 5 Hz (d), 12 Hz (q), 1 H), 1.25 (br s, 1 H, OH); ^{13}C NMR δ 132.8, 124.0, 73.7, 49.2, 47.4, 44.3, 31.5, 29.8, 25.3, 22.8 (C-3 not observed). *cis-exo*-**18b**: ^1H NMR δ ca. 2.05 (m, 1 H), ca. 1.92 (m, 1 H), 1.78 (br s, 1 H, OH), 1.78–1.61 (m, 2 H), 1.08 (m, 1 H); ^{13}C NMR δ 128.3, 127.2, 79.4, 48.6, 48.2, 47.4, 40.2 (C-3), 31.7, 25.2, 25.0, 22.6. *trans-endo*-**18b**: only obtained as a 2:1 mixture with the preceding isomer; ^1H NMR δ 2.30–2.12 (m, 3 H), 1.92 (m, 1 H), 1.34 (m, 1 H); ^{13}C NMR δ 130.8, 126.3, 72.4, 52.0, 47.9, 37.6 (C-3), 29.7, 27.1, 24.5, 22.6 (1 signal not observed because of overlap). *trans-exo*-**18b**: ^1H NMR δ 2.28–1.98 (m, 2 H), 1.71 (m, 1 H), 1.61 (br, 1 H, OH), 1.36 (m, 1 H), 1.23 (dt, J = 2.5 Hz (d), 12 Hz (t)).

2,3,3a,4,5,7a-Hexahydro-3,3,6-trimethyl-1*H*-inden-1-ol (18c). Alkali treatment of the pressure bottle was omitted: oven temperature 65–70 °C (0.5 Torr); ^1H NMR (in addition to Table II) δ 1.68 (s, CH_3 at C-6 of major isomer); IR ν 3349, 2926, 1449, 1366, 1075, 1032 cm^{-1}; MS m/z (%) 180 (42), 135 (33), 124 (67), 121 (73), 106 (88), 93 (88), 85 (70), 41 (100); HRMS calcd for $C_{12}H_{20}O$ 180.1514, found 180.1514.

From the forerun, **2,7,7-trimethyl-1,3,5,8-nonatetraene (22)** was obtained by evaporation and bulb-to-bulb distillation [oven temperature 50–65 °C (25 Torr)] as a colorless liquid (contaminated with some chlorobenzene), which is very sensitive to polymerization: ^1H NMR δ 6.27, 6.21 (AB q, B part split into d with J = 9 Hz, 2 H), 6.05 (dd, J = 9, 15.5 Hz, 1 H), 5.83 (dd, 1 H, 8-H), 5.74 (d, J = 15.5 Hz, 1 H), 5.00–4.92 (m, 1,9-H), 1.86 (s, 3 H, CH_3 at C-2), 1.14 (s, 6 H, CH_3 at C-7).

1,2,3,3a,4,4a,5,6,7,8a-Decahydro-3,3-dimethyl-*s*-indacen-1-ol (18d): oven temperature 75 °C (0.55 Torr); IR ν 3341, 2949, 1434, 1345, 1067, 859 cm^{-1}; MS m/z (%) 206 (63), 173 (38), 132 (83), 119 (89), 91 (83), 85 (51), 41 (100); HRMS calcd for $C_{14}H_{22}O$ 206.1671, found 206.1671.

6-Bromo-2,3,3a,4,5,7a-hexahydro-3,3-dimethyl-1*H*-inden-1-ol (18e): oven temperature 80–85 °C (0.13 Torr); IR ν 3343, 2952, 2928, 1647, 1636, 1366 cm^{-1}; MS m/z (%) 246, 244 (8, 8), 201, 199 (11, 12), 187, 185 (19, 18), 165 (21), 121 (73), 85 (100); HRMS calcd for $C_{11}H_{17}{}^{79}BrO$ 246.0442, found 246.0443. *cis-exo*-**18e**: To a suspension of 112 mg (0.284 mmol) of **27** in 3 mL of methanol was added 107 mg (ca. 0.35 mmol) of 85–90% KOH in 1 mL of methanol. The starting material dissolved within 15 min, and stirring was continued for 135 min; 2 g of SiO_2 was added, the mixture was evaporated, and the residue was applied on a short SiO_2 column and eluted with EtOAc/hexanes, 1:5, to obtain, after evaporation, 65 mg (93%) of the product as a colorless oil; ^1H NMR (in addition to Table II) δ 2.44–2.37 (m, 2 H), 1.77–1.61 (m, 3 H), 1.59 (s, 1 H, OH), 1.35 (tt, J = 8, 13.5 Hz, 1 H); ^{13}C NMR δ 129.6 (d, J = 163 Hz), 122.5 (s), 78.1 (d, J = 143 Hz), 50.9 (d), 48.5 (t), 45.8 (d), 39.9 (s), 35.0 (t, J = 132 Hz), 31.6 (q, J = 126 Hz), 25.2 (q), 24.7 (t); IR ν 3339, 2948, 1649, 1451, 1368, 1032, 729 cm^{-1}.

2,3,3a,4,5,7a-Hexahydro-3,3,7-trimethyl-1*H*-inden-1-ol (18f). The mixture of stereoisomers and ca. 6% of unreacted *Z*-**17f** could be separated by column chromatography on SiO_2 with EtOAc/hexanes, 1:10, into two fractions (R_f = 0.22 and 0.16), the first of which contained *Z*-**17f** and *trans-endo*-**18f**, the second (colorless solid, mp 63–70 °C) the two exo isomers: oven temperature 55–60 °C (0.5 Torr); ^1H NMR (methyl groups at C-7) *trans-endo*-**18f** δ 1.79; *cis-exo*-**18f** δ 1.83; *trans-exo*-**18f** δ 1.80. Fraction 2 was used for further characterization: IR ν 3308, 2924, 1445, 1383, 1364, 1075, 1030 cm^{-1}; MS m/z (%) 180 (19), 121 (44), 106 (64), 93 (100), 85 (40), 79 (31); HRMS calcd for $C_{12}H_{20}O$ 180.1514, found 180.1514.

2,3,3a,4,5,7a-Hexahydro-3,3,7a-trimethyl-1*H*-inden-1-ol (18g). The impure material obtained after a first chromatography (SiO_2, EtOAc/hexanes, 1:8) and bulb-to-bulb distillation was again chromatographed carefully (to remove a forerun; SiO_2, EtOAc/hexanes, 1:10, then 1:8). The residue after evaporation solidified and was sublimed in vacuo [60 °C (0.1 Torr)] to obtain colorless needles of ca. 95% pure major isomer: mp 66–66.5 °C; ^1H NMR δ 5.64, 5.59 (AB q, J = 10 Hz, A part split into t with J = 3–3.5 Hz, B part broadened; 2 H, 6,7-H), 3.95 (br dd, J = 5.5, 8 Hz, 1 H, 1-H), 2.07 to ca. 1.8 (m, 2 H), 1.80 (dd, J = 6, 12.5 Hz, 1 H, 2-H), 1.73 to ca. 1.55 (m, 3 H), 1.53 (dd, J = 8.5, 12.5 Hz, 1 H, 2-H), 1.38 (br s, 1 H, OH), 1.09, 1.03, 0.95 (each s, 3 H, CH_3); ^{13}C NMR δ 135.2 (d), 125.2 (d), 79.4 (d), 52.1 (d), 49.2 (t), 44.9 (s), 38.2 (s), 32.5 (q), 26.2 (q), 23.2, 23.1 (t, q or q, t), 20.7 (t); IR (solidified film) ν 3333, 2950, 2919, 1653, 1366, 1030 cm^{-1}; MS m/z (%) 180 (7), 136 (28), 121 (20), 106 (20), 95 (83), 85 (100); HRMS calcd for $C_{12}H_{20}O$ 180.1514, found 180.1514.

1-Butyl-2,3,3a,4,5,7a-hexahydro-3,3-dimethyl-1*H*-inden-1-ol (18h). A 70-mg sample of crude **17h** was cyclized according to the General Procedure. The crude product was chromatographed on SiO_2 (EtOAc/hexanes, 1:15, then 1:10, then 1:8) to obtain: (1) 7.1 mg of **12** (see under **17h**); (2) 14.2 mg of *cis-endo*-**18h**; (3) 24.8 mg of a 4:1 mixture of *trans-endo*- and *cis-exo*-**18h**; (4) 5.7 mg of *trans-exo*-**18h**. Fraction 3 was bulb-to-bulb distilled, oven temperature 75–80 °C (0.3 Torr). *cis-endo*-**18h**: ^1H NMR (in addition to Table II) δ 2.14 (m, 1 H), 1.96 (m, 1 H), 1.47 (br s, 1 H, OH), 1.70–1.23 (m, 9 H), 0.91 (t, J = 7 Hz, 3 H, CH_3); IR ν 3563, 3418, 3017, 2953, 2930, 2870 cm^{-1}. Fraction 3: MS m/z (%) 222 (3), 141 (81), 122 (55), 107 (45), 57 (78), 41 (100); HRMS calcd for $C_{15}H_{26}O$ 222.1984, found 222.1984. *trans-exo*-**18h**: ^1H NMR (in addition to Table II) δ 2.19 (m, 1 H), 2.07 (m, 1 H), 1.71

(m, 1 H), 1.60 (br s, 1 H, OH), ca. 1.6–1.2 (m, 8 H), 0.92 (t, J = 7 Hz, 3 H, CH_3); IR ν 3370, 3019, 2953, 2928, 2863 cm^{-1}.

5-[(*tert*-Butyldimethylsilyl)oxy]-4,7,7-trimethyl-1,3,8-nonatriene (20): To a solution of 195 mg (1.08 mmol) of **17h** and 184 mg (2.7 mmol) of imidazole in 0.5 mL of DMF was added at 0 °C all at once 196 mg (1.3 mmol) of *tert*-butylchlorodimethylsilane. The mixture was stirred at room temperature for 17 h and then filtered over a short SiO_2 column with EtOAc/hexanes, 1:25. Evaporation yielded 282 mg (89%) of **20** as a colorless oil: ^1H NMR δ 6.53 (m, 1 H, 2-H), 5.89 (d, J = 11 Hz, 1 H, 3-H), 5.14 (m, 1 H, 1c-H), 5.06 (m, 1 H, 1t-H), 4.91 (m, 1 H, 9t-H), 4.90 (m, 1 H, 9c-H), 4.08 (dd, J = 4.5, 7 Hz, 5-H), 1.70 (s, 3 H, CH_3 at C-4), 1.61, 1.46 (AB q, J = 14 Hz, both parts split into d with J = 7 and 4.5 Hz; 2 H, 6-H), 1.04, 1.00 (each s, 3 H, CH_3 at C-7), 0.87 (s, 9 H, *t*-Bu), 0.01, −0.07 (each s, 3 H, CH_3Si); IR ν 1256, 1075, 1057, 905, 837, 776 cm^{-1}; MS m/z (%) 237 (5, M − C_4H_9), 211 (9), 189 (24), 147 (100), 75 (63).

1-[(*tert*-Butyldimethylsilyl)oxy]-2,3,3a,4,5,7a-hexahydro-3,3,7a-trimethyl-1*H*-indene (21). A 39.5-mg sample (0.134 mmol) of **20** was cyclized in chlorobenzene at 260 °C for 48 h following the General Procedure for intramolecular Diels–Alder reactions (vide supra). The crude product was chromatographed on SiO_2 with EtOAc/hexanes, 1:30, and bulb-to-bulb distilled to obtain 18 mg (46%) of **21** as a colorless oil which contained ca. 6% of the starting material: oven temperature 95 °C (0.1 Torr); ^1H NMR δ 5.72, 5.67 (AB q, J = 10 Hz, A part broadened, B part split into t with J = 3 Hz; 7,6-H of minor isomer), 5.60, 5.55 (AB q, J = 10 Hz, A part split into t with J = 3.5 Hz, B part broadened; 6,7-H of major isomer), 3.85 (dd, J= 6, 7.5 Hz, 1-H of major isomer), 3.74 (dd, J = 6, 9 Hz, 1-H of minor isomer), 2.08–1.81, 1.75–1.38 (m, 2,3a,4,5-H) containing 1.66, 1.52 (AB q, J = 12.5 Hz, both parts split into d with J = 6 and 7.5 Hz; 2-H of major isomer), 1.08, 0.97, 0.94 (each s, CH_3 at C-3,7a of major isomer), 1.01, 0.87 (each s, two of the CH_3 at C-3,7a of minor isomer), 0.90 (s, *t*-Bu), 0.04, 0.03 (each s, CH_3Si of major isomer), 0.05, 0.01 (each s, CH_3Si of minor isomer).

5-(Benzyloxy)-7,7-dimethyl-1,3,8-nonatriene (22a). A solution of 166 mg (1 mmol) of **17b** in 1 mL of THF was added dropwise via syringe at 0 °C to 51 mg (1.02 mmol) of 50% NaH in 0.5 mL of THF. After 10 min at room temperature 18.5 mg (0.05 mmol) of tetrabutylammonium iodide was added, followed by 143 μL (1.2 mmol) of benzyl bromide. The reaction was allowed to proceed to room temperature for 5 h and then quenched with 3 drops of water. After evaporation, the residue was chromatographed on SiO_2 with EtOAc/hexanes, 1:25, and bulb-to-bulb distilled to obtain 173 mg (68%) of **22a** as a colorless oil: oven temperature 80 °C (0.5 Torr); ^1H NMR δ 7.40–7.22 (m, 5 H, Ph), 6.35 (m, 1 H, 2-H), 6.16 (dd, J = 10.5, 15 Hz, 1 H, 3-H), 5.82 (m, 1 H, 8-H), 5.69 (dd, J = 8, 15 Hz, 1 H, 4-H), 5.22 (m, 1 H, 9c-H), 5.10 (m, 1 H, 9t-H), 4.89 (m, 1 H, 1t-H), 4.88 (m, 1 H, 1c-H), 4.48, 4.27 (AB q, J = 11.5 Hz, 2 H, CH_2Ph), 3.83 (dt, 1 H, J = 4 Hz (d), 7.5 Hz (t), 1 H, 5-H), 1.76, 1.52 (AB q, J = 14.5 Hz, both parts split into d with J = 7.5 and 4 Hz; 2 H, 6-H), 1.05, 1.02 (each s, 3 H, CH_3); IR ν 1603, 1455, 1092, 1003, 907, 733, 696 cm^{-1}; MS m/z (%) 256 (0.3), 241 (0.8), 91 (100), 69 (97); HRMS calcd for $C_{17}H_{21}O$ (M − CH_3) 241.1592, found 241.1592.

5-[(*tert*-Butyldiphenylsilyl)oxy]-7,7-dimethyl-1,3,8-nonatriene (22b). To a solution of 33 mg (0.20 mmol) of **17b** and 18 mg (0.26 mmol) of imidazole in 0.2 mL of DMF was added at 0 °C 63 μL (0.24 mmol) of *tert*-butylchlorodiphenylsilane. After 5.5 h at room temperature, water was added, and the product was extracted into hexanes. Drying over $MgSO_4$ and evaporation gave the crude product, which was filtered over SiO_2 with EtOAc/hexanes, 1:25, and evaporated to obtain 73 mg (90%) of **22b** as a colorless oil: ^1H NMR δ 7.70–7.60, 7.45–7.30 (m, 4 + 6 H, Ph), 6.12 (m, 1 H, 2-H), 5.71–5.50 (m, 3 H, 3,4,8-H), 4.97, 4.95, 4.74, 4.73 (each m, 1 H, 1,9-H), 4.15 (dt, J = 4.5 Hz (d), 7.5 Hz (t), 1 H, 5-H), 1.67, 1.56 (AB q, J = 14 Hz, each part split into d with J = 4.5 and 7.5 Hz, 2 H, 6-H), 1.03 (s, 9 H, *t*-Bu), 0.85, 0.84 (each s, 3 H, CH_3); IR ν 1428, 1111, 1003, 909, 822, 739, 702 cm^{-1}; MS m/z (%) 404 (2.5), 347 (72), 267 (66), 200 (50), 199 (100), 187 (50); HRMS calcd for $C_{27}H_{36}OSi$ 404.2535, found 404.2537.

1-(Benzyloxy)-2,3,3a,4,5,7a-hexahydro-3,3-dimethyl-1*H*-indene (23a). Compound **25a** was cyclized according to the General Procedure, and the crude product was filtered over SiO_2 with EtOAc/hexanes, 1:25, and bulb-to-bulb distilled: oven temperature 130 °C (0.1 Torr); ^1H NMR δ 7.38–7.22 (m, 5 H, Ph), 6.00–5.53 (series of m) containing 5.90, 5.72 (each m; cis-exo isomer) (2 H, 6,7-H), 4.61–4.38 (series of AB q) containing 4.51, 4.47 (AB q, J = 14 Hz, cis-exo isomer) (2 H, CH_2Ph), 4.01 (ddd, J = 5.5, 6.5, 7.5 Hz), 3.88 (br q, J = 4 Hz), 3.75 (ddd, J = 3.5, 6.5, 8 Hz), 3.58 (ddd, J = 6, 8.5, 9.5 Hz) (1 H, 1-H, cis-endo, trans-endo, cis-exo, and trans-exo isomers), 2.76 (m, 7a-H of cis-exo isomer), 2.43 1.51, 1.46 to ca. 1.0 (series of m, 2,3a,4,5-H, and 7a-H of minor isomers), 1.17, 0.97 (cis-exo isomer), 1.00, 0.94 (trans-exo isomer), 1.10, 1.03, 0.97, 0.79 (remaining isomers) (3 H, CH_3); IR ν 2924, 1455, 1094, 1071, 733, 696 cm^{-1}; MS m/z (%) 256 (7), 178 (4), 165 (5), 147 (10), 121 (65), 91 (100); HRMS calcd for $C_{18}H_{24}O$ 256.1827, found 256.1827.

1-[(*tert*-Butyldiphenylsilyl)oxy]-2,3,3a,4,5,7a-hexahydro-3,3-dimethyl-1*H*-indene (23b). Compound **22b** was cyclized according to the General Procedure, and the crude product was filtered over SiO_2 with EtOAc/hexanes, 1:100: ^1H NMR δ 7.70–7.60, 7.43–7.31 (m, 4 + 6 H, Ph), 5.83–5.43 (series of m, 2 H, 6,7-H), 4.38 (br q, J = 6.5 Hz), 4.28 (m), 4.00 (ddd, J = 3.5, 6, 7.5 Hz), 3.82 (dt, J = 6 Hz (d), 9 Hz (t)) (1 H, 1-H, sequence of isomers as for **23a**), 2.85 (m, 7a-H of cis-exo isomer), 2.57, 2.41 to ca. 0.95 (series of m, H-2,3a,4,5, and 7a-H of minor isomers), 1.22, 0.87 (each s, CH_3 of cis-exo isomer), 1.05 (s, *t*-Bu of cis-exo isomer (+ others?)), 1.08, 1.04, 1.03, 1.00, 0.91, 0.70 (each s, CH_3 and *t*-Bu of minor isomers); IR ν 1428, 1111, 822, 738, 700 cm^{-1}; MS m/z (%) 403 (0.2, M − H), 389 (0.7), 347 (99), 269 (24), 199 (100), 121 (75); HRMS calcd for $C_{23}H_{27}OSi$ (M − C_4H_9) 347.1831, found 347.1830.

***cis-exo*-6-Bromo-2,3,3a,4,5,7a-hexahydro-3,3-dimethyl-1-[(*p*-nitrobenzoyl)oxy]-1*H*-indene (27)**. To a solution of 270 mg (1.1 mmol) of **18e** (mixture of isomers) and 5 mg (0.04 mmol) of 4-(dimethylamino)pyridine in 1.1 mL of pyridine was added all at once at 0 °C 225 mg (1.21 mmol) of *p*-nitrobenzoyl chloride. After 70 min at room temperature, CH_2Cl_2 and 30 mL of 10% $KHSO_4$ solution were added; the aqueous phase was further extracted with CH_2Cl_2, and the combined organic phases were dried over $MgSO_4$. Evaporation yielded 393 mg (91%) of solid crude product as a mixture of isomers, which was recrystallized from 12 mL and again from 5 mL of boiling $CHCl_3$/hexanes, 1:5; crystallization was each time allowed to proceed at room temperature. In this way, 185 mg (43%; 91% relative to the cis-exo content of **18e**) of stereochemically homogeneous **27** was obtained, which formed thin, rectangular, colorless plates suitable for X-ray crystallography: mp 139.5–140.5 °C; ^1H NMR δ 8.30, 8.20 (AB q, J = 9 Hz, 4 H, C_6H_4), 6.35 (br d, J = 5 Hz, 1 H, 7-H), 5.18 (ddd, J = 2.5, 6, 8.5 Hz, 1 H, 1-H), 2.99 (m, 1 H, 7a-H), 2.47–2.41 (m, 2 H, 5-H), 2.19 (dd, J = 8.5, 14.5 Hz, 1 H, 2-H), 1.87–1.76 (m, 2 H, 3a,4-H), 1.66 (dd, J = 2.5, 14.5 Hz, 1 H, 2-H), 1.38 (ddt, J = 6.5 Hz (d), 9.5 Hz (d), 14 Hz (t), 1 H, 4-H), 1.22, 1.05 (each s, 3 H, CH_3); IR (Nujol) ν 1713, 1607, 1522, 1289, 729 cm^{-1}; MS m/z (%) 314 (0.3, M − Br), 228, 226 (89, 93), 213, 211 (60, 58), 150 (82), 147 (100), 104 (74). Anal. Calcd for $C_{18}H_{20}BrNO_4$: C, 54.84; H, 5.11; Br, 20.27; N, 3.55. Found: C, 54.64; H, 5.32; Br, 19.77; N, 3.65.

2-(1-Hydroxy-3,3-dimethyl-4-pentenyl)furan (29). To 4 mL (5.4 mmol) of *n*-butyllithium (1.35 M in hexanes) and 5 mL of THF was added at −20 °C 0.44 mL (6 mmol) of furan. The mixture was stirred while the temperature was allowed to rise to +15 °C within 1 h, and at this temperature for another 30 min. After cooling in an acetone/CO_2 bath, 0.67 mL (5 mmol) of 3,3-dimethyl-4-pentenal[13] was added, and the mixture was stirred at −78 °C for 30 min and then quenched with NH_4Cl solution. Workup with brine and ether, drying over $MgSO_4$, chromatography on SiO_2 (EtOAc/hexanes, 2:7), and bulb-to-bulb distillation yielded 0.72 g (80%) of **29** as a colorless oil: oven temperature 50–55 °C (0.55 Torr); ^1H NMR δ 7.35 (dd, J = 1, 2 Hz, 1 H, 1-H of furan), 6.31 (dd, J = 2, 3 Hz, 2-H of furan), 6.20 (d, J = 3 Hz, $J_{1,3}$ not resolved, 1 H, 3-H of furan), 5.90 (m, 1 H, 4-H), 5.00 (m, 1 H, 5c-H), 4.99 (m, 1 H, 5t-H), 4.79 (ddd, J = 4, 5, 7 Hz, 1 H, 1-H), 2.02 (d, J = 4 Hz, 1 H, OH), 1.96–1.86 (m, 2 H, 2-H), 1.08, 1.06 (each s, 3 H, CH_3); IR ν 3385, 1640, 1153, 1008, 913, 738 cm^{-1}; MS m/z (%) 180 (3), 162 (17), 110 (60), 97 (91), 69 (46), 41 (100);

HRMS calcd for $C_{11}H_{14}O$ (M - OH) 162.1045, found 162.1045.

6-Hydroxy-3,3-dimethyl-1,7-octadien-4-one (30) was prepared on a 5-mmolar scale according to the General Procedure for directed aldol condensations (vide supra) from 3,3-dimethyl-4-penten-2-one[15] and acrolein. The crude product was filtered over SiO_2 with EtOAc/hexanes, 1:3, and bulb-to-bulb distilled to obtained 0.56 g (67%) of **30** as a colorless liquid: oven temperature 50–55 °C (0.75 Torr); ^1H NMR δ 5.89 (m, 1 H, 2-H), 5.84 (m, 1 H, 7-H), 5.28, 5.18, 5.17, 5.12 (each m, 1 H, 1,8-H), 4.52 (m, 1 H, 6-H), 3.18 (d, J = 3.5 Hz, 1 H, OH), 2.72, 2.67 (AB q, J = 18 Hz, both parts split into d with J = 4 and 8 Hz, 2 H, 5-H), 1.24 (s, 6 H, CH_3); ^{13}C NMR δ 213.5 (s), 141.8 (d, J = 156 Hz), 139.1 (d, J = 154 Hz), 114.9 (t), 114.8 (t), 68.6 (d, J = 146 Hz), 50.9 (s), 43.8 (t, J = 126 Hz), 23.2 (q, J = 128 Hz); IR ν 3447, 1707, 1636, 1073, 994, 922 cm^{-1}; MS m/z (%) 169 (0.5, M + H), 150 (0.5), 99 (10), 81 (100), 43 (100); HRMS calcd for $C_{10}H_{14}O$ (M - H_2O) 150.1045, found 150.1044.

3,3-Dimethyl-1,5,7-octatrien-4-one (31) was prepared from **30** on a 2.9-mmolar scale in 25% yield by method B (vide supra) or on a 2.3-mmolar scale in 71% yield by method C as a yellow liquid: oven temperature 65 °C (10 Torr); ^1H NMR δ 7.24 (dd, J = 11, 14.5 Hz, 1 H, 6-H), 6.50 (d, J = 15 Hz, 1 H, 5-H), 6.45 (m, 1 H, 7-H), 5.92 (m, 1 H, 2-H), 5.65 (m, 1 H, 8c-H), 5.52 (m, 1 H, 8t-H), 5.18 (m, 2 H, 1-H), 1.25 (s, 6 H, CH_3); IR ν 1686, 1619, 1590, 1266, 1076, 1011, 920 cm^{-1}; MS m/z (%) 150 (2.5), 135 (1), 81 (100), 69 (19), 53 (36); HRMS calcd for $C_{10}H_{14}O$ 150.1045, found 150.1045.

3,3-Dimethyl-1,5,7-octatrien-4-ol (32) was prepared from **31** by the General Procedure for $LiAlH_4$ reductions (vide supra) on a 0.3-mmolar scale in 97% yield: oven temperature 80–85 °C (9 Torr); ^1H NMR δ 6.35 (m, 1 H, 7-H), 6.24 (dd, J = 10.5, 15 Hz, 1 H, 6-H), 5.86 (m, 1 H, 2-H), 5.73 (dd, J = 7, 15 Hz, 1 H, 5-H), 5.22 (m, 1 H, 8c-H), 5.13 (m, 1 H, 1t-H), 5.10 (m, 1 H, 8t-H), 5.08 (m, 1 H, 1c-H), 3.85 (br d, J = 6.5 Hz, 1 H, 4-H), 1.64 (br s, 1 H, OH), 1.03, 1.01 (each s, 3 H, CH_3); ^{13}C NMR δ 144.6 (d, J = 151 Hz), 136.2 (d, J = 151 Hz), 132.9 (d, J = 152 Hz), 132.4 (d, J = 153 Hz), 116.8 (t, J = 157 Hz), 112.9 (t, J = 156 Hz), 78.5 (d, J = 144 Hz), 41.3 (s), 23.2 (q, J = 126 Hz), 16.9 (q, J = 126 Hz); IR ν 3409, 1640, 1603, 1096, 1005, 911 cm^{-1}; MS m/z (%) 151 (0.5, M - H), 135 (1), 83 (27), 69 (64), 59 (75), 45 (100); HRMS calcd for $C_{10}H_{15}$ (M - OH) 135.1174, found 135.1174.

Thermal rearrangement of 32 was conducted on a 0.16-mmolar scale at 195 °C for 16.5 h as described in the General Procedure for intramolecular Diels–Alder reactions (vide supra). Chromatography on SiO_2 with EtOAc/hexanes, 1:12, yielded 2.0 mg (8%) of a product, followed by 5.5 mg (22%) of starting material. The product was assumed to be **6-methyl-3-vinyl-5-heptenal (33)** on the basis of the following ^1H NMR spectrum: δ 9.71 (t, J = 2.5 Hz, 1 H, CHO), 5.74 (m, 1 H, vinyl-CH_2), 5.09 (br t, overlapping, 1 H, 5-H), 5.04 (m, 1 H, cis-H of vinyl-CH_2), 5.03 (m, 1 H, trans-H of vinyl-CH_2), 2.67 (br quint, J = 7 Hz, 1 H, 3-H), 2.47, 2.38 (AB q, J = 14.5 Hz, both parts split into dd with J = 2, 5.5 Hz and 2.5, 8 Hz, 2 H, 2-H), 2.10 (t, J = 7 Hz, 2 H, 4-H), 1.70, 1.59 (each s, 3 H, CH_3).

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Supplementary Material Available: Selected ^1H and ^{13}C NMR spectra and an X-ray structure analysis of **27** (90 pages). Ordering information is given on any current masthead page.

Synthesis and Conformation of Dithia[3]metacyclo[3]thiophenophanes and [2]Metacyclo[2]thiophenophanes

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Dithia[3]metacyclo[3]- -(2,3)-, -(2,4)-, -(2,5)-, and -(3,4)thiophenophanes were prepared by dithiol bis-alkylations and were oxidized with *m*-chloroperbenzoic acid to the corresponding tetraoxides. Pyrolysis of the tetraoxides under a reduced pressure gave the corresponding [2]metacyclo[2]thiophenophanes together with many unexpected compounds. The conformations of the obtained products are also discussed.

Although many heterophanes and some metacyclo- and paracycloheterophanes such as metacyclopyridinophanes[1] have been prepared and their physical properties investigated,[2] there are only a few reports[3] about [*n*]metacyclo[*n*]heterophanes which contain 5-membered aromatic rings. Since [2]metacyclo[2]thiophenophanes ([2.2]phanes) have not yet been reported, the properties and the reactions of these compounds are still unknown. It has been previously reported that[4] [2.2]metacyclophanes could be easily prepared and that these compounds show novel reactivities and chemical structures.

There are four possible isomers of [2.2]phanes: (2,3)-phane, (2,4)phane, (2,5)phane, and (3,4)phane as shown in Figure 1.

Although these phanes could be important synthetic intermediates for the preparation of the corresponding [*n*]metacyclophanes by the reductive thiophene ring-opening reaction and are interesting compounds in the field of organic physical chemistry, their preparation and

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