pling), nonprotonic Lewis acid-base type solvent effects parallel type-B hydrogen bonding (proton sharing) effects in their dependence on β. Moreover, it may also be noted that for the 50-odd correlations of properties of protonic indicators or reactants which we have carried out in connection with the HBA basicity scale, the demonstrated fits with β or with β and π^* were better than corresponding correlations with DN or with AN and DN. Indeed, from our evaluation of the latter parameter, we conclude that DN is a reasonably good measure of the ability of the solvent to serve as an electron-pair donor to solutes when only oxygen bases (and a few R-CN nitrogen bases) are considered but that the correlations of solvent effects on free-energy-proportional properties are likely to break down if the solvent sets include single bonded nitrogen or pyridine bases.

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Registry No. Triethylamine, 121-44-8; $Et_3N-SbCl_5$ complex, 75896-34-3.

Systematic Conformational Analysis. General Method for Rapid Conformational Evaluation. Its Application to the Hydroazulene System

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A simple yet general method for conformational analysis of cyclic systems, with present focus on the seven-membered ring, is outlined. From a two-dimensional structure, with stereocenters indicated by wedged and hashed bonds, a semiquantitative conformational evaluation is rapidly performed by hand. Central in the procedure stands the identification of torsion-constraining structural features and the analysis of the constraints in terms of allowed signs and magnitudes of endocyclic torsion angles. The matching of the so-defined constraints against a set of basic unsubstituted ring forms allows for the derivation of a primary set of allowed conformations or, via simultaneous assessment of conformational energies (i.e., strain energies of the unsubstituted ring form and axial substituents), a secondary set of probable forms. The final prediction of the preferred conformation(s) proceeds via supplementary energy and torsional constraint evaluations. Examples are given dealing with the hydroazulene system.

Molecular model examination is extremely popular among synthetic chemists because it can yield both qualitative (e.g., evaluation of steric environment) and quantitative (e.g., interatomic distances) information that may otherwise be difficult to arrive at. A prerequisite to the effective use of models, however, is the knowledge of the preferred geometry of the molecule. Hence a problem arises when dealing with systems that can adopt several conformations. Indeed, the sole manipulation of a model does not indicate which among the considered forms is the preferred one, nor can it ensure that all possible conformations have been examined. The present paper describes a conformational procedure that intends to help in resolving that problem in a ready and systematic way.

At the origin of this work stands the observation of some remarkable stereo- and regioselective reactions in the hydroazulene field.[2] In contrast with the six-membered-ring case,[3-5] the conformational analysis of seven-membered rings and other flexible systems is generally regarded as tentative. A conformational procedure for cycloheptane derivatives with particular attention to the natural perhydroazulenes has already been reported by Hendrickson.[6] A refinement of his procedure has presently led to a general yet simple method for the semiquantitative conformational analysis of cyclic systems. Starting from a two-dimensional structure with stereocenters indicated by the conventional wedged (β, up)/hashed (α, down) bond notation, one can perform the analysis rapidly by hand. In this paper I describe the essential features of the method with focus on the seven-membered ring.

As a working hypothesis I assume that the analysis of the torsional constraint imposed upon a cyclic system must enable the deduction of a primary set of "allowed" basic conformations (Chart I, entry 9). A basic conformation refers to a geometrically well-defined (usually symmetry related) form. Structural features which may impose a torsion constraint on the endocyclic bonds include fusions with other rings, bridgings, and anchoring substituents (e.g., *tert*-butyl) located off the ring (entry 5). The consideration of the strain energies[7,8] of the unsubstituted ring forms and of the various substituents (entry 10) in the allowed forms leads to a secondary set of "probable" low energy conformations (entry 12). Further energy and torsion constraint evaluations (entries 13 and 14) eventually yield the preferred geometry of the molecule (entry 15). Torsion constraints may restrict both the sign and the magnitude of internal torsion angles of a ring and are

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[1] Bevoegdverklaard Navorser of the Belgian Nationaal Fonds voor Wetenschappelijk Onderzoek.

[2] For recent syntheses of pseudoguaianolides, see: (a) Demuynck, M.; De Clercq, P.; Vandewalle, M. *J. Org. Chem.* **1979**, *44*, 4863; (b) Kok, P.; De Clercq, P.; Vandewalle, M. *Ibid.* **1979**, *44*, 4553; (c) Wender, P. A.; Eissenstat, M. A.; Filosa, M. P. *J. Am. Chem. Soc.* **1979**, *101*, 2196; (d) Grieco, P. A.; Ohfune, Y.; Majetich, G. *Tetrahedron Lett.* **1979**, 3265. (e) Grieco, P. A.; Ohfune, Y.; Majetich, G. *J. Org. Chem.* **1979**, *44*, 3092. (f) Roberts, M. R.; Schlessinger, R. H. *J. Am. Chem. Soc.* **1979**, *101*, 7626; (g) Quallich, G. J.; Schlessinger, R. H. *Ibid.* **1979**, *101*, 7627.

[3] Barton, D. H. R. *Experientia* **1950**, *6*, 316.

[4] Eliel, E. L. "Stereochemistry of Carbon Compounds"; McGraw-Hill: New York, 1972.

[5] Eliel, E. L. *J. Chem. Educ.* **1975**, *52*, 762.

[6] Hendrickson, J. B. *Tetrahedron* **1963**, *19*, 1387.

[7] (a) Bucourt, R. *Bull. Soc. Chim. Fr.* **1962**, 1983. (b) *Ibid.* **1963**, 1262. (c) *Ibid.* **1964**, 2080. (d) Bucourt, R.; Hainaut, D. *Ibid.* **1965**, 1366. For a review, see: (e) Bucourt, R. *Top. Stereochem.* **1974**, *8*, 159.

[8] (a) Hendrickson, J. B. *J. Am. Chem. Soc.* **1961**, *83*, 4537. (b) *Ibid.* **1962**, *84*, 3355. (c) *Ibid.* **1963**, *85*, 4059. (d) *Tetrahedron* **1963**, *19*, 1387. (e) *J. Am. Chem. Soc.* **1967**, *89*, 7036. (f) *Ibid.* **1967**, *89*, 7043.

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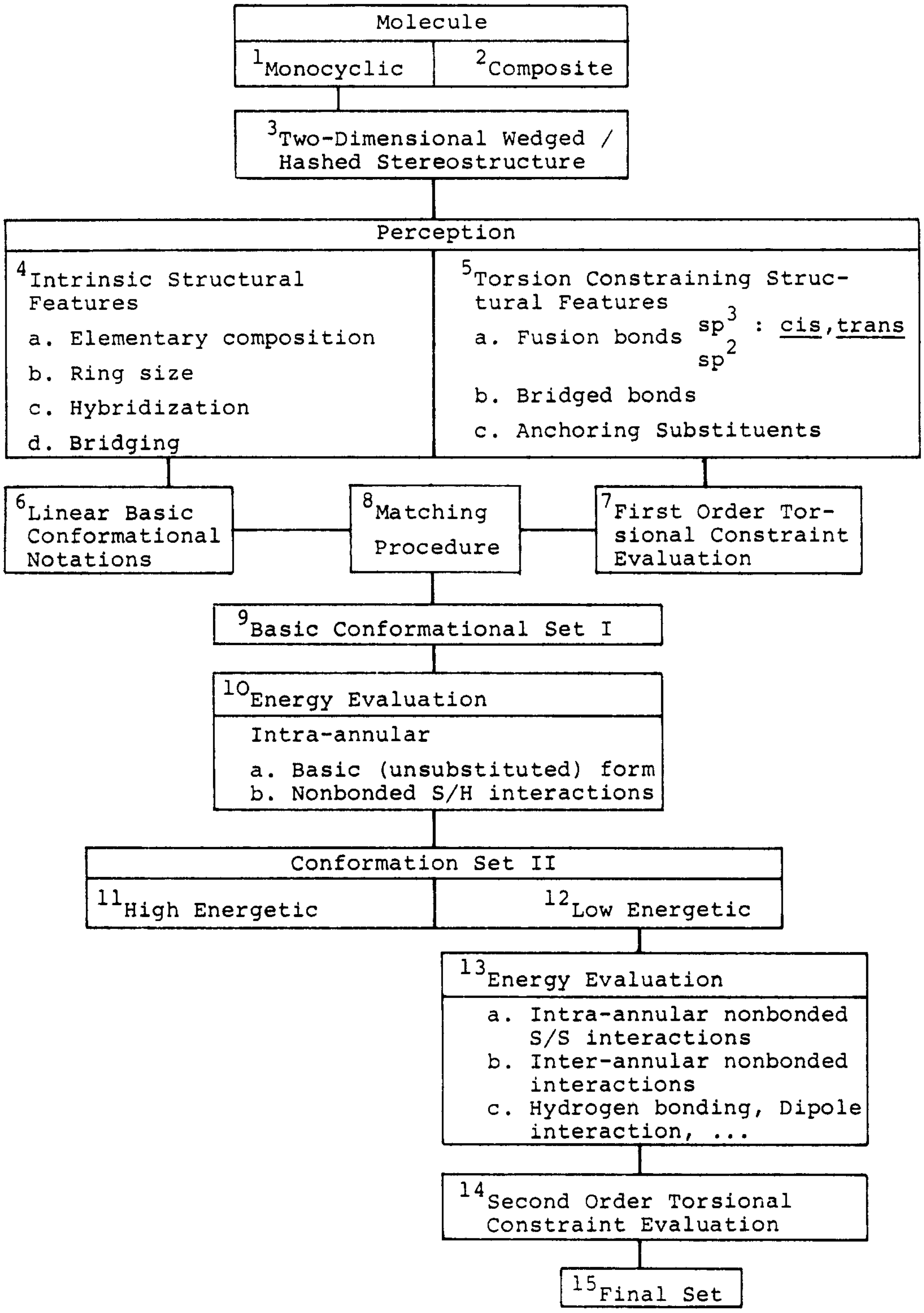
Chart I. Generalized Conformational Procedure



accordingly analyzed (entry 7). The crucial deduction (entry 8) of the primary set implies that the basic conformations of any unsubstituted cycle, as characterized by its intrinsic structural features (entry 4), be defined by the sign and the magnitude of its torsion angles. For this purpose a linear conformational notation is introduced in which actual angle magnitudes are represented by dihedral angle types.

Torsion constraint originating from anchoring substituents and from fusions involving sp^3 atoms is analyzed in part I. Dihedral angle types and linear conformational notations for seven-membered-ring forms are introduced in parts II and III, respectively. In part IV the procedure for conformational deduction is outlined. Finally, the full procedure is exemplified for the hydroazulene system in part V.

I. Torsion Constraint Evaluation

A torsion-constraining structural feature imposes a restriction on the sign or the magnitude (or both) of an endocyclic torsion angle. It is further shown that a torsion restriction may depend critically on the configuration. Since the direct application of the procedure to a two-dimensional structure is required, it is necessary to define the relationship between substituent orientation (indicated by wedged and hashed bonds) and endocyclic torsion angle

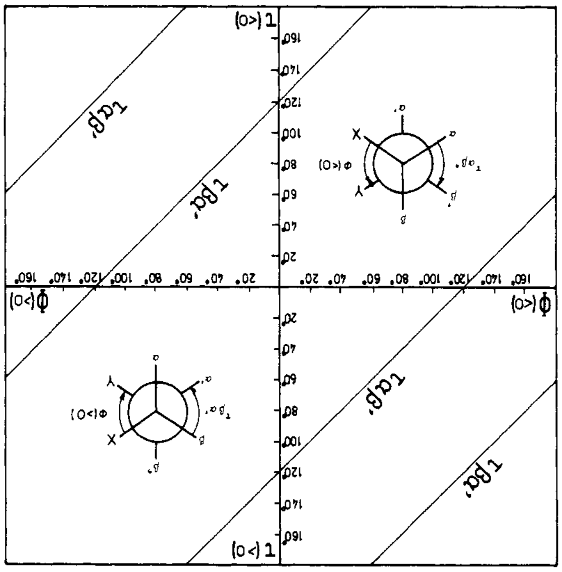


Figure 1. Relationship between dihedral angles $\tau_{\alpha\beta'}$ and $\tau_{\beta\alpha'}$ (defining relative substituent orientation) and the endocyclic torsion angle ϕ within the cyclic fragment X–C(β,α)–C′(β',α')–Y (clockwise around the cycle from C to C′).

in terms of the equatorial–axial distinction and the common β (up) and α (down) notation of substituent positions.

β,α Notation and the Torsion Angle ϕ. In an sp^3-hybridized cyclic fragment X–C–C′–Y the internal or endocyclic torsion angle at C,C′ is defined as the angle (ϕ) between the vector XC and the vector C′Y when viewed along C–C′ (Figure 1); the sign of ϕ is positive if XC is to be rotated clockwise into C′Y and negative if counterclockwise.[9] When applying the procedure on a particular cycle (or fragment), we will always consider the different atoms of the cycle clockwise.[10] The spatial orientation of the substituents on C (and C′) are defined by β and α (and β' and α'), being respectively up and down at the given atoms when the ring is viewed from above as in the steroid convention. If τ represents the dihedral angle between the substituents β,α and β',α' (see the Newman projections in Figure 1), then the relation between $\tau_{\beta\beta'}$, $\tau_{\alpha\alpha'}$, $\tau_{\beta\alpha'}$, $\tau_{\alpha\beta'}$, and ϕ (algebraic values) is given by equations 1–3,

$$\text{cis:}\quad \tau_{\beta\beta'} = \tau_{\alpha\alpha'} = \phi \qquad (1)$$

$$\text{trans:}\quad \tau_{\beta\alpha'} = -(120° - \phi) \qquad (2)$$

$$\text{trans:}\quad \tau_{\alpha\beta'} = +(120° + \phi) \qquad (3)$$

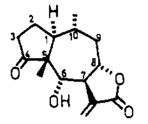
$$(0° \leq |\tau| \leq 180°)^{11}$$

assuming trigonal symmetry. A ring fusion at a bond with torsion angle ϕ can thus occur between β and β' or between α and α' in the case of a cis fusion and between β and α' or between α and β' in the case of a trans fusion. From Figure 1 it can be directly deduced that the sign of ϕ at a trans fusion is dictated by the configuration of the junction atoms, provided that the fused cycles do not posses basic conformations with torsion angles larger than 120° (absolute value):[12] an $\alpha\beta'$ configuration of the cycle fused at ϕ implies both a negative torsion angle at the fusion bond in the original cycle ($\phi < 0$) and a positive torsion angle in the fused cycle ($\tau_{\alpha\beta'} > 0$), whereas a $\beta\alpha'$ configuration implies a positive ϕ and a negative $\tau_{\beta\alpha'}$. In carpesiolin (1) the sign of $\phi_{5,1}$ and $\phi_{8,7}$ in the seven-membered ring is thus negative since at both bonds we have trans fusions with five-membered rings of the type $\alpha\beta'$. Obviously the same conclusion is arrived at when it is considered that the cycloheptane is fused at both five-membered rings. In contrast, the sign of ϕ at a cis fusion is not directly related to the configuration of the junction atoms: $\tau_{\alpha\alpha'}$ and $\tau_{\beta\beta'}$ should be represented by the same diagonal in Figure 1. Similar relationships may be derived for fusions where the junction atoms are sp^2 hybridized.

Table I. Dihedral Angle Types and Their Corresponding Values (in Degrees)[a]

OO (0–9)	*CC* (60–69)	*O* (0–19)
OA (10–19)	*CD* (70–79)	*A* (10–39)
AA (20–29)	*DD* (80–89)	*B* (30–59)
AB (30–39)	*DE* (90–99)	*C* (50–79)
BB (40–49)	*EE* (100–110)	*D* (70–99)
BC (50–59)		*E* (90–110)

[a] The two-letter types correspond to 10° ranges, and the one-letter types are so derived as to encompass the corresponding two-letter types; e.g., the range of type *A* encompasses the ranges of types *OA*, *AA*, and *AB*.



1

Axial–Equatorial Notation and the Torsion Angle ϕ. The axial–equatorial distinction for a substituent is readily made provided that the sign and the magnitude of the flanking endocyclic dihedral angles are known.[7e] For our present purpose it suffices to remember that a β-oriented substituent at any carbon of a ring is axial if, when reading clockwise, it lies between bond dihedral angles of signs (+,–), (0,–), or (+,0) and equatorial if between (–,+), (0,+), or (–,0). If flanked by bonds with torsion angles of the same sign, both substituents on a carbon are of equal (strain free) energy; they are termed isoclinal when, moreover, both angles are equal in magnitude.[8f]

Upon analysis of torsional constraints, distinction is made between first- and second-order evaluation (cf. Chart I, entries 7 and 14). During first-order evaluation the *allowed signs and magnitudes* of the different endocyclic torsion angles ϕ are evaluated. With regard to the sign, a torsion constraint is identified when a particular sign for ϕ is imposed or rejected. An sp^3 trans fusion between cycles smaller than eight membered (obviously the case in hydroazulenes) is an example of sign imposition, whereas an imposed equatorial (or axial) position of a substituent is a case of sign rejection (anchoring substituents). Which sign is imposed or rejected is configurationally dependent (vide supra). With regard to its magnitude, a torsional constraint will merely be determined by the ring size (vide infra).

During second-order evaluation the *preferred magnitudes* of endocyclic torsion angles are considered on the base of specific structural features of the ring; examples thereabout are given in part V.

II. Dihedral Angle Types

In order to allow for the ready comparison of allowed torsion angle magnitudes with those actually encountered

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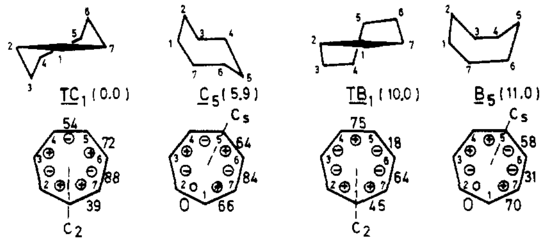
(9) The symbol ϕ will exclusively be used for the dihedral angle made by three consecutive cyclic bonds.

(10) The clockwise reading of a cycle is not necessary for the determination of the sign of an endocyclic torsion angle; it is, however, crucial for all further deductions.

(11) Values of $|\tau|$ larger than 180° are conveniently reduced by $\tau_{\alpha\beta'} = -240° + \phi$ and $\tau_{\beta\alpha'} = 240° + \phi$. The sign of τ is dictated by the clockwise (positive) or anticlockwise (negative) rotation (Figure 1).

(12) Cycloalkanes which are smaller than eight-membered do not possess basic forms with torsion angles larger than 120°.[8e]

Chart II. Conformational Diagrams[a] of the Basic Cycloheptane Forms According to Hendrickson[8e]



[a] The subscript used in the symbol defining a particular form (twist–chair TC, chair C, twist–boat TB, and boat B) indicates the atom sectioned by the symmetry element. Torsion angles are given in degrees. Strain energies are given in parentheses in kilojoules per mole.

in the basic conformations of a cycle, we further define the magnitude of a dihedral angle by an angle type.

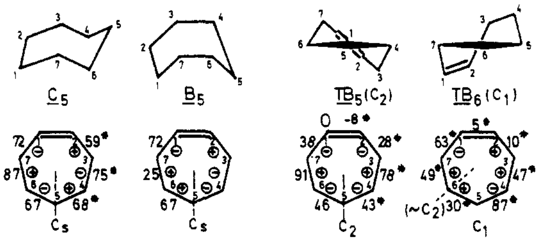
The 0–180° scale is divided in equal parts comprising ranges of 10° (absolute values); each range is characterized by a double capital letter (Table I).[13] This scale division is particularly covenient for practical use especially when one notes the following features: (i) types identified by two identical letters (i.e., *OO*, *AA*, etc.) refer to an even number of tens, and those identified by different letters to an odd number of tens; (ii) the smaller values are identified by the first letters of the alphabet, except for values around or equal to 0° which correspond to type *OO*; (iii) the letters *O* and *E*, *A* and *D*, *B* and *C*, respectively, are complementary when dealing with trans fusions where K equals 110° instead of 120° ($K = |\phi| + |\tau_{\alpha\beta'}|$ or $|\phi| + |\tau_{\beta\alpha'}|$).[14,15] Thus in carpesiolin (1) a dihedral angle type *AB* at bond 1,5 in the five-membered ring corresponds to type *CD* (complementary for $K = 110°$) at the same bond in the seven-membered ring and vice versa. Types corresponding to values larger than 110° are not considered here since we are merely interested in seven-membered and smaller rings.[12] Single letter types which correspond to broader ranges are also included in Table I; they will be used when torsion angles of basic conformations are not well defined (vide infra; cycloheptene model).

III. Linear Conformational Notations of the Basic Seven-Membered-Ring Forms

The above-defined dihedral angle types (Table I) are now applied to the definition of the basic conformations of the seven-membered ring.

Cycloheptane Model.[16] Both chair and boat forms of cycloheptane are flexible and undergo pseudorotation. In each family it is generally accepted that the twist form with an axis of symmetry (C_2) is the most stable and the pure chair or boat form with a plane of symmetry (C_s) the least stable conformer. The conformational diagrams of the four symmetrical cycloheptane forms (twist–chair, TC; chair, C; twist–boat, TB; boat, B) as derived by machine computation[8e] are shown in Chart II. Applying the types defined in Table I to the torsion angle values of the four basic forms leads to the linear notations shown in Table II. This representation consisting of successive signs and types of torsion angles of a cycle will further be referred to as a linear conformational notation. A particular form is characterized by a letter symbol defining the type conformation and a subscript indicating the atom sectioned by the symmetry element. In the linear notation this atom is indicated by //.[17] The eight forms of Table II are thus TC$_1$, C$_5$, TC$_2$, C$_6$, TB$_1$, B$_5$, TB$_2$, and B$_6$. It is important to note that this set of eight forms enables the recognition of the 56 symmetrical forms that are encountered during the entire TC–C and TC–B pseudorotations and thus, in practice, of *all* symmetrical forms which can be adopted by a cycloheptane.[18] This is brought about by (i) the duplication of angle types in the linear notation and (ii) by the inclusion of the mirror-image notations (indicated by a prime in the tables). For each form in Table II are also given the strain energies associated with an axial

Chart III. Conformational Diagrams[a] of the Basic Cycloheptene Forms According to Favini et al.[21g] and/or Elmer and Lifson[b] [21d]



[a] The subscript in the definition of a form indicates the atom sectioned by the symmetry element, pseudo-C_2 for TB(C_1). Rounded torsion angles are given in degrees.
[b] Indicated with an asterisk.

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[13] For a division of the entire 360° scale in six equal parts, allowing ±30° for a torsion angle, see: Klyne, W.; Prelog, V. *Experientia* **1960**, *16*, 521.

[14] In steroids K is a function of the substitution pattern at the junction bond in the case of fusion between two six-membered rings; at the C/D junction K averages 109°.[15] From X-ray results on hydroazulene derivatives it follows that for a trans fusion between a seven- and five-membered ring K averages 111° in the case of a carbocyclic system and 115° in the case of a γ-lactone (as in 1); the equality rule (cf. eq 1) is generally respected (unpublished results).

[15] Geise, H. J.; Altona, C.; Romers, C. *Tetrahedron* 1967, *23*, 439.

[16] For leading references, see: (a) Allinger, N. L. *J. Am. Chem. Soc.* **1959**, *81*, 5727; (b) Pauncz, R.; Ginsburg, D. *Tetrahedron* **1960**, *9*, 40; (c) Bixon, M.; Lifson, S.; *Ibid.* **1967**, *23*, 769; (d) Glazer, E. S.; Knorr, R.; Ganter, C.; Roberts, J. D. *J. Am. Chem.* Soc. **1972**, *94*, 6026; (e) McPhail, A. T.; Sim, G. A. *Tetrahedron* **1973**, *29*, 1751. (f) Flapper, W. M. J.; Romers, C. *Ibid.* **1975**, *31*, 1705; (g) Bocian, D. F.; Pickett, H. M.; Rounds, T. C.; Strauss, H. L. *J. Am. Chem. Soc.* **1975**, *97*, 687. (h) Bocian, D. F.; Strauss, H. L. *Ibid.* **1977**, *99*, 2876; (i) Birnbaum, G. I.; Buchanan, G. W.; Morin, F. G. *Ibid.* **1977**, *99*, 6652. (j) Offenbach, J. L.; Strauss, H. L.; Graverson-Demilly, D. *J. Chem. Phys.* **1978**, *69*, 3441; (k) Dillen, J.; Geise, H. J. *Ibid.* **1979**, *70*, 425. See also ref 6 and 8d–f.

[17] An "octant rule"-type projection (cf. footnote 35 in ref 24b) can be used for differentiating between mirror-image conformations possessing a diad axis (e.g. TC and TB cycloheptane): the ring is disposed symmetrically in "positive" (indicated by subscript +) or "negative" (indicated by –) octants with the atom, sectioned by the axis, located at the quadrant intersection position. Conformations possessing a symmetry plane are unambiguously identified by noting the atom, sectioned by the symmetry plane, as a superscript when that atom lies above the mean plane of the molecule and a subscript when lying under that plane; this particular notation is commonly used in five-membered rings; i.e., see: Altona, C.; Sundaralingam, M. *J. Am. Chem. Soc.* **1972**, *94*, 8205. Both symbol types are readily deduced from a linear conformational notation by simple consideration of the sign of the angles at the bonds flanking the atom (//) sectioned by the symmetry element: C_2, the "octant sign" is opposite to the sign of the flanking torsion angles, C_s, a (+,–) clockwise (or from left to right in the linear notation) reading of the sign of the flanking angles indicates that the atom is above the plane, while a (–,+) succession is indicative for the atom lying under the plane.

[18] The TC–C forms given in Table II are adjacent in the pseudorotation continuum (TC ⇌ C ⇌ TC′ ⇌ C′), and their linear notations allow for the visualization of the changes in magnitude of torsion angles during pseudorotation. On the other hand, the TB and B forms in Table II (i.e., TB, B, TB′, and B′) are not adjacent forms; in fact, between each form two symmetrical forms are encountered (the first and fourth forms represent the TB and B forms in Table II; see ref 16f and footnote 15 in ref 8g):

TB:	*+BB*	*−CC*	*−OA*	*+CD*	*−OA*	*−CC*	*+BB* /
B:	*+AB*	*−CD*	*±OO*	*+CD*	*−AB*	*−BC* /	*+BC*
TB:	*+OA*	*−CD*	*+OA*	*+CC*	*−BB* /	*−BB*	*+CC*
B:	*±OO*	*−CD*	*+AB*	*+BC* /	*−BC*	*−AB*	*+CD*

Table II. Linear Conformational Notations of the Four Symmetrical Cycloheptane Conformations[a]

atom[b]		2		3		4		5		6		7		1		2		3		4		5		6		7	
ϕ[c]	1,2		2,3		3,4		4,5		5,6		6,7		7,1		1,2		2,3		3,4		4,5		5,6		6,7		7,1
		10				6				12						10				6				12			
TC(0)	+*AB*		−*DD*		+*CD*		−*BC*		+*CD*		−*DD*		+*AB*	//	+*AB*		−*DD*		+*CD*		−*BC*		+*CD*		−*DD*		+*AB*
				12				6				10						12				6				10	
		4				2				2				4		4				2				2			
C(6)	±*OO*		−*CC*		+*DD*		−*CC*	//	+*CC*		−*DD*		+*CC*		±*OO*		−*CC*		+*DD*		−*CC*	//	+*CC*		−*DD*		+*CC*
				16				4				16						16				4				16	
						12				6				10						12				6			
TC′(0)	−*AB*	//	−*AB*		+*DD*		−*CD*		+*BC*		−*CD*		+*DD*		−*AB*	//	−*AB*		+*DD*		−*CD*		+*BC*		−*CD*		+*DD*
				10				6				12						10				6				12	
						16				4				16						16				4			
C′(6)	−*CC*		±*OO*		+*CC*		−*DD*		+*CC*	//	−*CC*		+*DD*		−*CC*		±*OO*		+*CC*		−*DD*		+*CC*	//	−*CC*		+*DD*
		4		4				2				2				4		4				2				2	
		18						20								18						20					
TB(10)	+*BB*		−*CC*		−*OA*		+*CD*		−*OA*		−*CC*		+*BB*	//	+*BB*		−*CC*		−*OA*		+*CD*		−*OA*		−*CC*		+*BB*
						20						18								20						18	
		18						20						18		18						20					
B(11)	±*OO*		−*CD*		+*AB*		+*BC*	//	−*BC*		−*AB*		+*CD*		±*OO*		−*CD*		+*AB*		+*BC*	//	−*BC*		−*AB*		+*CD*
				6								6						6								6	
								20						18								20					
TB′(10)	−*BB*	//	−*BB*		+*CC*		+*OA*		−*CD*		+*OA*		+*CC*		−*BB*	//	−*BB*		+*CC*		+*OA*		−*CD*		+*OA*		+*CC*
				18						20								18						20			
						6								6						6							
B′(11)	−*CD*		±*OO*		+*CD*		−*AB*		−*BC*	//	+*BC*		+*AB*		−*CD*		±*OO*		+*CD*		−*AB*		−*BC*	//	+*BC*		+*AB*
		18		18						20						18		18						20			

[a] For each basic form are given the angle types (Table I) according to the torsion angle values calculated by Hendrickson (Chart II), the strain in the ring itself (values in parentheses in kilojoules/mole), and the strain energies (in kilojoules/mole) for an axial methyl group at the different possible locations, the β substituents being indicated in the upper row and the α substituents in the lower row; the latter energy values, calculated by Hendrickson, are in excess of strain in the ring itself and are rounded off.[8f] A prime indicates a mirror-image form and // the carbon atom sectioned by the symmetry element (C_2 for TC and TB, C_s for C and B). [b] Atom numbering according to Chart II. [c] Endocyclic torsion angles (ϕ) are indicated by the two atoms of the central bond; e.g., 1,2 stands for the dihedral angle C(7)–C(1)–C(2)–C(3).

Table III. Linear Conformational Notations of the Basic Cycloheptene Conformations[a]

	endocyclic torsion angles[b]																			
	1,2	2,3	3,4		4,5		5,6		6,7	7,1	1,2	2,3	3,4		4,5		5,6		6,7	7,1
C	*OO*	*+C*	*−D*		*+C*	//	*−C*		*+D*	*−C*	*OO*	*+C*	*−D*		*+C*	//	*−C*		*+D*	*−C*
C′	*OO*	*−C*	*+D*		*−C*	//	*+C*		*−D*	*+C*	*OO*	*−C*	*+D*		*−C*	//	*+C*		*−D*	*+C*
B	*OO*	*+C*	*−A*		*−C*	//	*+C*		*+A*	*−C*	*OO*	*+C*	*−A*		*−C*	//	*+C*		*+A*	*−C*
B′	*OO*	*−C*	*+A*		*+C*	//	*−C*		*−A*	*+C*	*OO*	*−C*	*+A*		*+C*	//	*−C*		*−A*	*+C*
TB(C_2)	*OO*	*−A*	*+D*		*−B*	//	*−B*		*+D*	*−A*	*OO*	*−A*	*+D*		*−B*	//	*−B*		*+D*	*−A*
TB′(C_2)	*OO*	*+A*	*−D*		*+B*	//	*+B*		*−D*	*+A*	*OO*	*+A*	*−D*		*+B*	//	*+B*		*−D*	*+A*
TB(C_1)	*OO*	*+O*	*+B*		*−D*		*+A*	//	*+B*	*−C*	*OO*	*+O*	*+B*		*−D*		*+A*	//	*+B*	*−C*
	OO	*−C*	*+B*	//	*+A*		*−D*		*+B*	*+O*	*OO*	*−C*	*+B*	//	*+A*		*−D*		*+B*	*+O*
TB′(C_1)	*OO*	*−O*	*−B*		*+D*		*−A*	//	*−B*	*+C*	*OO*	*−O*	*−B*		*+D*		*−A*	//	*−B*	*+C*
	OO	*+C*	*−B*	//	*−A*		*+D*		*−B*	*−O*	*OO*	*+C*	*−B*	//	*−A*		*+D*		*−B*	*−O*

[a] For each form are given the angle types (Table I) according to the torsion angle values calculated by Favini;[21g] in cases where one value corresponds to two one-letter types (e.g., 72.2°, 37.6°, and 91.3°), the choice of the angle type was dictated by the values given by Lifson.[21d] A prime indicates a mirror image conformation and // the carbon atom sectioned by the symmetry element (C_2 for TB and C_s for C and B) or the pseudosymmetry element (C_2 for TB(C_1)). [b] Endocyclic torsion angles (ϕ) are indicated by the two atoms of the central bond; e.g., 1,2 stands for the dihedral angle C(7)-C(1)-C(2)-C(3) (Chart III).

methyl substituent located on the seven possible atoms;[8f] the values given in the upper row are for β-oriented substituents and in the lower row for α-oriented substituents (e.g., 10 in the first row of the TC notation in Table II indicates a strain energy of 10 kJ/mol[19] for a β-oriented methyl group located at C(2). The strain energy of the ring form itself (relative to TC) is given in parentheses. An important advantage of using angle types instead of exact dihedral angle values resides in the possibility of using the same type when different values are found in the literature.[20]

Cycloheptene Model.[21] For the present purpose the C_s chair form (C), in the boat family the C_s form (B), and two twisted forms, TB(C_2) and TB(C_1), are retained as basic forms (Chart III). The latter form yields four linear notations (Table III). Since disparate values for the torsion angle magnitudes of the different basic forms are found in the literature,[22] single-letter types are used for their characterization in the linear notations. The chair form is generally considered to be the most stable conformation of cycloheptene. There exists, however, a disagreement in the literature concerning the evaluation of the strain energy of the remaining forms.[23] Moreover the strain energies of axial substituents in these forms are not exactly known. The different forms will therefore be considered only qualitatively in further work: C, TB(C_2), TB(C_1), and B in decreasing order of stability.

Cycloheptanone Model .[24] As a result of a recent study,[24g] it appears that the notations in Table II can be used for cycloheptanones and that the preferred conformations of cycloheptan-1-one are, in order of decreasing stability: TC$_1$, TC$_2$, C$_4$ (0–1); TC$_3$, TC$_4$ (7–8); TB$_4$ (9); C$_2$, C$_3$ (10). The subscript refers to the atom sectioned by the symmetry element when the carbonyl is located at C(1). The values in parentheses are the strain energies of the basic unsubstituted forms; when dealing with cycloheptanones these values will be used instead of the values given in Table II for cycloheptanes. Conformations other than the ones cited above (i.e., C$_1$, remaining TB forms, B forms) will not be considered since they are too high in energy. It should also be reminded that the substituent strain energies given in Table II are overestimated in the cycloheptanone case due to the absence of axial substitution at the carbonyl position.

IV. Matching Procedure

In this part the procedure is described which allows for a rapid conformational deduction, taking into account (i) the torsional constraints that were evaluated for the cyclic system and (ii) the linear conformational notations for the corresponding model (Tables II and III).

The matching procedure is exemplified for 1. The two trans fusions with five-membered rings of the type $\alpha\beta'$ impose on the C(8)–C(7) and C(5)–C(1) bonds of the cycloheptane a torsion angle of negative sign (vide supra; Figure 1) with a magnitude corresponding to types *BC*, *CC*, *CD*, or *DD* (i.e., larger than 55°, corresponding to a minimal *K* value of 105° minus a maximal ϕ value of 50° in the five-membered ring). Possible types *DE* and *EE* are omitted here since these types are not encountered in the linear notations of the basic cycloheptane forms. β substitution on the cycloheptane is present at C(1), C(7), and C(5) and α substitution at C(10), C(8), C(6), and C(5). One notes the following "before matching":

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(19) Throughout this paper kilojoules/mole will be used instead of the usual kilocalories/mole (1 kcal = 4.18 kJ); since we will essentially be dealing with semiquantitative work, the values in kilojoules are further rounded to the nearest whole number.

(20) The torsion angle types given in Table II are in excellent accordance with the available literature data. Compare, e.g., the values given in Table I of ref 16f and in Table V of ref 16i. The strain energies used in Table II[8e] show larger differences with other reported values: see, e.g., Table IV in ref 16k for the C form (~4 kJ/mol instead of the further used 6 kJ/mol).

(21) For a review, see: (a) Tochtermann, W. *Fortschr. Chem. Forsch.* **1970**, *15*, 378. For other leading references, see: (b) Pauncz, R.; Ginsburg, D. *Tetrahedron* **1960**, *9*, 40; (c) Allinger, N. L.; Sprague, J. T. *J. Am. Chem. Soc.* **1972**, *94*, 5734; (d) Ermer, O.; Lifson, S. *Ibid.* **1973**, *95*, 4121; (e) Favini, G.; Nava, A. *Theor. Chim. Acta* **1973**, *31*, 261; (f) Zuccarello, F.; Buemi, G.; Favini, C. *J. Mol. Struct.* **1973**, *18*, 295; (g) Favini, G.; Buemi, G.; Raimondi, M.; *Ibid.* **1978**, *2*, 137; (h) White, D. N. J.; Bovill, M. J. *J. Chem. Soc., Perkin Trans. 2* **1977**, 1610; (i) Foulani, P.; Clement, C. *Bull. Soc. Chim. Fr.* **1971**, 3444; (j) St-Jacques, M.; Vaziri, C. *Can. J. Chem.* **1973**, *51*, 1192.

(22) Torsion angles for cyclohept-1-ene vary between the following values: for the chair,[21d,g–i] $\phi_{2,3}$ = 58–72°, $\phi_{3,4}$ = 74–88°, $\phi_{4,5}$ = 67–73°; for the boat,[21g] $\phi_{2,3}$ = 69–72°, $\phi_{3,4}$ = 21–25°, $\phi_{4,5}$ = 67–73°; for the twist-boat (C_2), $\phi_{2,3}$ = 28–38°, $\phi_{3,4}$ = 78–91°, $\phi_{4,5}$ = 43–46°.

(23) Published energy values (in kilojoules/mole) relative to chair cycloheptene: TB(C_2), 2.38,[21c] 1.76,[21d] 7.15,[21g] and 6.27;[21h] TB(C_1), 11.04;[21d] B, 14.09[21c] and 4.97.[21g]

(24) For leading references, see: (a) Allinger, N. L. *J. Am. Chem. Soc.* **1959**, *81*, 5727; (b) Jones, J. B.; Zander, J. M.; Price, P. *Ibid.* **1967**, *89*, 94; (c) Kirk, D. N. *J. Chem. Soc., Perkin Trans. 1* **1977**, 2122; (d) Lightner, D. A.; Docks, E. L. *Tetrahedron* **1979**, *35*, 713. (e) Allinger, N. L.; Tribble, M. T.; Miller, M. A. *Ibid.* **1972**, *28*, 1173; (f) St-Jacques, M.; Vaziri, C.; Frenette, D. A.; Goursot, A.; Fliszár, S. *J. Am. Chem. Soc.* **1976**, *98*, 5759; (g) Bocian, D. F.; Strauss, H. L. *J. Chem. Phys.* **1977**, *67*, 1071; (h) Ayotte, L.; St-Amour, R.; St-Jacques, M.; Hull, W. E. *Tetrahedron Lett.* **1980**, 793.

i	5,1		1,10		10,9		9,8		8,7		7,6		6,5		5,1
ii				00		00		00				00			
iii	–								–						–
iv		00				00			/2	00			/2		

In the first row (i) is given the numbering of the endocyclic torsion angles of the cycloheptane (clockwise); the spaces in between refer to the numbering of the ring atoms (not noted). In all examples, the numbering currently in use for hydroazulenic sesquiterpenes shall be used (see 1). In the third row (iii) one notes the imposed torsional strain restrictions on the cycloheptane, in the present case – at 5,1 and 8,7 (explicitly) and types *BC*, *CC*, *CD*, or *DD* at these bonds (implicitly). The data in the second (ii) and fourth (iv) rows will enable one to calculate the strain energies of the different substituents in each deduced form. For that purpose 00 is filled in row ii at the carbon atoms which lack a β substituent and in row iv at the atoms which lack an α substituent. A /2 is noted in the case of oxygen substitution: whereas all carbon substituents are assigned the full methyl value, oxygen substituents, as the α-oriented C(6) and C(8) substituents, are assigned half the methyl value (cf. Winstein's *A* values[25]). Rows i–iv as a whole are now matched against the corresponding rows of the eight forms given in Table II, looking for concordance in row iii. One of the six forms that are found is encountered for C′ and one reads for this particular form "upon matching":

i	5,1		1,10		10,9		9,8		8,7		7,6		6,5		5,1
ii				00		00		00				00		16	
iii	−*DD*		+*CC*	//	−*CC*		+*DD*		−*CC*		±*OO*		+*CC*		−*DD*
iv		00				00			/2	00		4	/2		

Concordance is here found for $\phi_{5,1}$ and $\phi_{8,7}$ equal to −*DD* and −*CC*, respectively. All necessary information concerning this particular form can now be deduced: (i) identification of the form as C_{10} since the form is found for C′ in the above table and // is located at C(10); (ii) the total strain energy for axial substitution as 18 kJ/mol (sum of 16 and 4/2); (iii) the total strain energy of the conformation as 24 kJ/mol, being the sum of the substituent strain energy (18 kJ/mol) and the energy of the form itself (6 kJ/mol for a C conformation); (iv) the dihedral angle type corresponding to each cyclic bond of the molecule in that conformation. The six deduced forms are identical with the ones found for 2 and 3 (Table IV). Due to the special format used in Tables II and III, the deduction of *every* allowable conformation is secured. Furthermore, the process can be done rapidly by hand when one is using a transparent paper.[26]

V. Application of the Full Procedure

The stepwise procedure for conformational analysis of a cyclic system (e.g., the seven-membered ring) comprises four distinct stages (cf. Chart I). (1) The first is first-order torsion constraint evaluation, i.e., the analysis of torsional constraints imposed on the seven-membered ring in terms of allowed signs and types of torsion angles at the endocyclic bonds (part I). (2) The second is deduction of the primary set of allowed basic conformations (part IV). (3) The third is the deduction of the secondary set of probable (low energy) forms via first-order energy evaluation of each deduced form in the primary set. Conformations of high energy are discarded and include conformations possessing a total strain energy larger than 8 kJ/mol compared to the lowest energetic form in the primary set (a larger than 95% preponderance at room temperature) and conformations possessing a total strain energy larger than 16 kJ/mol (relative to unsubstituted twist–chair cycloheptane). For synthetic purposes it is safe to allow for a difference of at least 8 kJ/mol between two forms; indeed, the introduced strain energies (Table II) have been obtained in the past by means of molecular mechanics, and any shortcomings in the force field used may seriously affect these values.[20,23] On the other hand, "energetically preferred" forms with total strain energies larger than 16 kJ/mol (usually a result from severe syn-diaxial nonbonded interactions) tend to depart from the predicted ideal geometry by torsion angle deformation.[7d] It should be noted that in the cycloheptane and cycloheptanone cases the matching procedure outlined in part IV (using Table II) can lead *directly* to the secondary set. (4) The fourth is deduction of the preferred conformation via second-order-energy and torsion-constraint evaluation, whenever more than one form is retained in the secondary low-energy conformational set. At this stage of the procedure a more detailed analysis of torsional constraints resulting from specific structural features of the molecule is performed in terms of *preferred* dihedral angle types at certain bonds (vide infra). With regard to final energy evaluation, caution should be exercized especially in cases where low-lying conformers are predicted to have approximately equal energies; in practice, the synthetic chemist should not place much trust in differences of ~4 kJ/mol (vide supra). Finally, several possible interactions should be identified by molecular model examination of the total molecule in the remaining conformations: intraannular nonbonded substituent interactions, interannular nonbonded interactions, dipole interactions, hydrogen bonding. Their contribution to the total energy of the considered form is, for the time being, merely qualitatively evaluated.

Composite systems, as hydroazulenes, may in principle be analyzed in two different ways. For each ring of the composite system a primary or secondary set may be derived, the allowed combinations for both rings retained, and the so-obtained conformations of the total molecule further analyzed. In the hydroazulene case, however, it is more convenient to perform the analysis on the seven-membered ring alone and to consider five-membered rings merely as torsion constraining structural features. The latter approach is illustrated for 2 and 3. The seven-membered ring being identically substituted, the same

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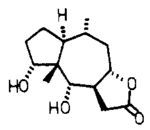
[25] Winstein, N.; Holness, N. J. *J. Am. Chem. Soc.* **1955**, *77*, 5562.

[26] The data noted as "before matching" in the text are written on the transparent paper in the format shown in Table II. The paper is then moved, going from the left to the right along each of the eight linear notations of Table II and looking for concordance of the imposed signs *and* types. When concordance is found, and thus an allowed form deduced, one can read all information of interest (noted as "upon matching" in the text) directly from the table through the transparent paper.

Table IV. Allowed Conformations (Primary Set) of the Cycloheptane in 2 and 3 and Their Strain Energies[a]

	endocyclic torsion angles									
	5,1	1,10	10,9	9,8	8,7	7,6	6,5	5,1	E_s[b]	E_{tot}[c]
C_9	−*CC*	+*DD*	−*CC* //	+*CC*	−*DD*	+*CC*	±*OO*	−*CC*	4	10
TC_6	−*DD*	+*CD*	−*BC*	+*CD*	−*DD*	+*AB* //	+*AB*	−*DD*	10	10
C_{10}	−*DD*	//			−*CC*				18	24
TB_6	−*CC*				−*CC*	//			38	48
B_5	−*BC*				−*CD*		//		26	37
B_7					−*BC* //				24	35
2[d]	−68 (−*CC*)	+78 (+*CD*)	−54 (−*BC*)	+65 (+*CC*)	−91 (−*DE*)	+67 (+*CC*)	+1 (+*OO*)			
3[d]	−86 (−*DD*)	+69 (+*CC*)	−50 (−*BC*)	+70 (+*CD*)	−90 (−*DE*)	+42 (+*BB*)	+34 (+*AB*)			

[a] Deduced from Table II. [b] Substituent strain energy (kilojoule/mole) deduced from Table II. [c] Total strain energy (kilojoules/mole) is E_s plus the strain of the ring conformation relative to the TC form: C, B, and TB equal to 6, 11, and 10 kJ/mol, respectively. [d] Rounded off values (kilojoules/mole) as determined by X-ray crystallography[28] and their corresponding angle types.



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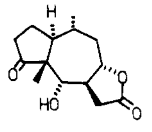

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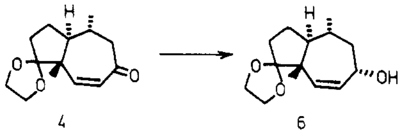
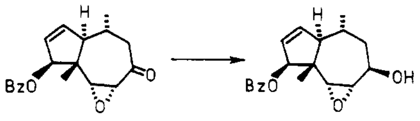
analysis for defining the torsional strain restrictions applies in the primary instance to both compounds. The presence of two trans-fused five-membered rings imposes on the cycloheptane bonds C(5)–C(1) and C(8)–C(7) torsion angles of types *BC*, *CC*, *CD*, or *DD* with a negative sign (vide supra). A matching of these possibilities with the linear notations of Table II leads to the primary set: TC_6, C_9, C_{10}, TB_6, B_5, and B_7 (Table IV). Two of these are low in energy (secondary set): 10 kJ/mol for TC_6 and C_9. Since the only crucial difference between these two pseudorotating forms is the magnitude of the torsion angle at C(5)–C(1), i.e., type *DD* for the former and type *CC* for the latter conformation, the final preference between these forms will be dictated by the nature of the cyclopentane ring. Due to the preferred staggered disposition around the central junction bond, the torsion angle at C(1)–C(5) in the five-membered ring will be as large as possible (i.e., of type *BB*).[27] The presence of a carbonyl at C(4) in product 3 induces, however, a flattening in the cyclopentane and hence a smaller angle at the fusion position.[24e] The best fitting at the junction bond is thus attained for a C_9 cycloheptane conformation in the case of product 2 (*CC* type corresponds to a *BB* in the five-membered ring for $K = 110°$) and a TC_6 form in the case of product 3 (*DD* type corresponding to *AA* in the cyclopentanone). A confirmation of this rationale is provided by the results of the X-ray diffraction study of lactones 2[28a] and 3:[28b] except for small differences in the fragment C(10)–C(6), 2 approximates almost perfectly the C_9 form and 3 the TC_6 form (Table IV).

As a further illustration a rationale is given for the following synthetic observations (see supplementary material): (a) enone 4 yields alcohol 6[2b] whereas the epimeric



4 6



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configuration (7) is obtained from the "corresponding" epoxide 5;[2d,e] (b) lactonization of 8 proceeds selectively, i.e., 9 vs. 10;[2b] (c) the equilibrium mixture of 11 and 12 is in favor of the trans-fused compound.[29]

Conclusion

A simple procedure for rapid by-hand conformational analysis of the seven-membered-ring system has been outlined. It has been shown that by comparing the tor-

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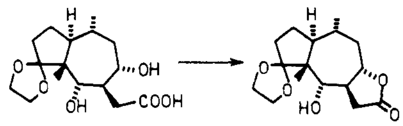
[27] A value of 50° probably corresponds to the maximum torsion angle in fused five-membered rings. See, e.g.: Altona, C.; Geise, H. J.; Romers, C. *Tetrahedron* **1968**, *24*, 13.

[28] (a) Declercq, J. P.; Germain, G.; Van Meerssche, M.; Kok, P.; De Clercq, P.; Vandewalle, M. *Acta Crystallogr., Sect. B* **1980**, *B36*, 190. (b) *Ibid.* **1980**, *B36*, 739.

[29] House, H. O.; Yau C.-C.; Van Derveer, D. *J. Org. Chem.* **1979**, *44*, 3031.

J. Org. Chem. 1981, 46, 675–678



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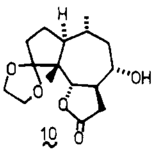

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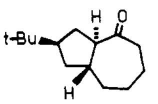

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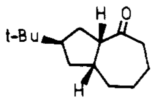

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sional constraints that are imposed upon a cyclic system with the basic ring conformations of the cycle, a primary set of allowed conformations can readily be deduced. The following features have been included in the procedure in order to allow for rapid deduction: torsional constraint evaluation, directly from the α (hashed bond) and β (wedged bond) configurational pattern of the two-dimensional structure; dihedral angle types as a measure for torsion angle magnitudes; linear conformational notations for the unambiguous definition of a conformation in terms of signs and magnitudes of torsion angles at endocyclic bonds. It has been shown that energy and further torsional constraint evaluation reduces effectively the allowable conformations to a small number of preferred ones.

The basic concepts used in the procedure should allow for extension of the present method to other ring systems and for treatment by computer as well.[30] Work on further applications of the present methodology is currently in progress.

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Registry No. 1, 63568-73-0; 2, 75765-40-1; 3, 73590-08-6; 4, 75765-41-2; 5, 75717-45-2; 8, 75717-46-3; 9, 75766-21-1; 10, 75717-47-4; 11, 70775-29-0; 11 tosylhydrazone, 75765-42-3; 12, 70775-28-9; 12 (*p*-bromophenyl)sulfonylhydrazone, 75765-43-4; cycloheptane, 291-64-5; cycloheptene, 628-92-2.

Supplementary Material Available: A detailed discussion (including Table V) of some observed selectivities in the hydroazulene field: formation of 6 and 7 from 4 and 5, respectively; selective lactonization of 8 to 9; favored formation of 11 in the equilibrium mixture of 11 and 12 (7 pages). Ordering information is given on any current masthead page.

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[30] Upon completion of this work a computer method for the semiquantitative assignment of the conformation of six-membered ring systems has been reported: Corey, E. J.; Feiner, N. F. *J. Org. Chem.* **1980**, *45*, 757, 765.

Phenaleno[1,9-*cd*][1,2,6]thiadiazinium Cation

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The title ion was prepared in solution in concentrated sulfuric acid by protonation–dehydration of phenaleno[1,9-*cd*][1,2,6]thiadiazine 2-oxide. Its spectral properties (^{1}H NMR, ^{13}C NMR, and UV–visible) have been measured and compared to those for similar ionic systems. The ^{13}C NMR data provided evidence for substantial sulfur d-orbital participation in the overall electronic description of the molecule. The electroreduction of the title species permitted the observation of the phenalenothiadiazinyl radical ESR spectrum. The hyperfine coupling constants provide evidence for spin delocalization into the heteroring portion of the molecule.

Interest in fused ring systems developed in two separate, albeit, closely related directions. In the first, chemists continue their quest for new compounds exhibiting unique physical and chemical properties. In the second emphasis is on the classification of aromaticity based upon molecular conformity with Hückel's rule.[1] Our delvings in this area have emphasized the perturbations caused by insertion of heteroatoms into fused, cyclic conjugated systems. In particular, our attention has centered on the synthesis and examination of tetracyclic peri-bridged napthalenes containing the -NSN-[2] and -NSeN-[3] linkages for the purpose of comparing their properties with those of their known isoelectronic, all-carbon analogues or as predictors of properties of as yet unknown compounds.

Thus, we previously prepared naphthol[1,8-*cd*:4,5-*c′d′*]bis[1,2,6]thiadiazine[2a] (1) and naphtho[1,8-*cd*:4,5-*c′d′*]bis[1,2,6]selenadiazine[3a] (2) as congeners of dipleiadiene (3), a substance which has received theoretical attention[4] but which thus far has defied the preparative chemists.[5]

The molecular and electronic structures of 1 and 2 as deduced spectroscopically[2a,3a] and confirmed by X-ray crystallography[2b,3b] show a strong bond-length alternation, particularly around the periphery of the molecule. This result intuitively leads the chemist to the conclusion that 1 and 2 are antiaromatic 16π systems, one which is at odds

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[1] (a) Hückel, E. *Z. Phys.* **1931**, *70*, 204; (b) *Ibid.* **1931**, *72*, 310. (c) Hückel, E. "Grundzüge der Theorie ungesättiger und Aromatisher Verbindungen"; Verlag Chemie: Berlin, 1938.

[2] (a) Haddon, R. C.; Kaplan, M. L.; Marshall, J. H. *J. Am. Chem. Soc.* **1978**, *100*, 1235. (b) Gieren, A.; Lamm, V.; Haddon, R. C.; Kaplan, M. L. *Ibid.* **1979**, *101*, 7277.

[3] (a) Kaplan, M. L.; Haddon, R. C.; Schilling, F. C.; Marshall, J. H.; Bramwell, F. B. *J. Am. Chem. Soc.* **1979**, *101*, 3306. (b) Gieren, A.; Lamm, V.; Haddon, R. C.; Kaplan, M. L. *Ibid.* **1980**, *102*, 5070.

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