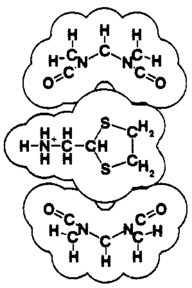

Figure 5. Conjectured cross-sectional representation of ligand–receptor complex for $C_{24}H_{36}N_{24}O_{12}\cdot c\text{-}(CH_2S)_2CHCH_2NH_3^+$. Outlines as in Figure 2. Interatomic distances within ligand correspond to projections for a puckered ring filling (nearly) the cavity.

energies could be systematically referenced to the vapor state. In sum, while it appears that the thioether linkage may indeed have a higher affinity for a hydrocarbon environment than does a methylene residue, it also has a corresponding higher attraction for an aqueous environment, according to the evidence developed by Hine.[7] The calculations of Fersht and Dingwall, supposedly demonstrating the unique importance of dispersion forces in thiasubstrate binding, do not refer to transfer from aqueous medium to the enzyme surface, as does their data. In their theoretical estimation they made no allowance for the fact of preferential aqueous solvation of S relative to CH_2, $2.3RT[\log \gamma(S) - \log \gamma(CH_2)] = 3.4$ kcal/mol, which apparently is able to negate the higher stability attainable for thioether complexes, as we find to be the case. We conclude that concerning the practical enzymological aspects of *hydrophobic* binding phenomena, a thioether linkage *is* a surrogate for a methylene unit, and the two are unlikely to be distinguishable except by some specific interaction, such as enzymic metal ion coordination.[11]

Putting the foregoing digression aside, we should like to emphasize that the thioethers are indeed excellent ligands for cucurbituril. Dithiolanylmethylamine (no. 24) provides the strongest binding ligand containing a single ammonium ion that we have yet encountered (absolute value for $K_f = 5.9 \times 10^5$ M^{-1}). In Figure 5 we show a cross-sectional representation of its complex with cucurbituril, illustrating the snugness of fit ("close-packing" of atoms), which we believe to be responsible for its exceptional ligand properties.

In conclusion, we should like to single out the most significant aspect of noncovalent binding emerging from this investigation. The high selectivities noted for the inclusion of alkylammonium ions within cucurbituril arise from the zonal nature of the interior of cucurbituril. The very center of the molecule evidently provides a lipophilic environment, yet the vicinity of the carbonyl oxygens surrounding the portals of the cage structure are especially lipophobic (to an equal extent, energywise). Consequently there is a sharp cut-off in alkyl group affinity as molecular size (chain length) of the ligand increases. The crystal structure of cucurbituril provides a partial explanation. A water molecule is found coordinated at each portal (in ammonium ion fashion), and these are linked by hydrogen bonds to a third H_2O at the center of the cavity.[2,12] Clearly, displacement of this central water molecule by ligand hydrocarbon should be exergonic (a hydrophobic effect). However, displacement of water from the polarized region of the carbonyls evidently is countervailingly endergonic. (This is in addition to any direct interactions between ligand and receptor within the complex.) It is the close juxtaposition of hydrophobic and hydrophilic regions within cucurbituril that *doubles* the selectivity that is ordinarily obtainable in transferring hydrocarbons from aqueous to lipidlike environment. We think it highly likely that biological receptors should be able to take advantage of this phenomenon. Proteins are replete with the appropriate functionality (hydrocarbon side chains plus carboxamide dipoles). In this respect, cucurbituril is a uniquely informative biochemical model system.

Acknowledgment. This work was supported by the Dow Chemical Co. Foundation, the University of Illinois Research Board, and (in part) by the Office of Naval Research.

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Ab Initio Calculations of the Olefin Strain Energies of Some Pyramidalized Alkenes[†]

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Contribution from the Department of Chemistry, University of Washington, Seattle, Washington 98195. Received October 26, 1987

Abstract: The olefin strain energies (OSEs) of four members (**10**, **1–3**) of a homologous series of pyramidalized, tricyclic alkenes have been computed as the difference between their hydrogenation energies and that of the bicyclic reference compound (**9**). The effects of double-bond pyramidalization on the optimized geometries and on the HOMO and LUMO orbital energies are discussed. The OSEs of cubene (**11**) and tricyclo[3.1.0.$0^{2,6}$]hex-1(6)-ene (**12**) have also been calculated; and, for comparison, the OSEs of bicyclo[2.2.0]hex-1(4)-ene (**13**) and bicyclo[1.1.0]but-1(3)-ene (**14**) have been computed, too. It is found that, in contrast to the series of alkenes comprised of **10** and **1–3**, most of the OSE in **11** and **12** is already present in their bicyclic counterparts. As a consequence of the relative ease of pyramidalizing the double bond in **13**, the OSE of cubene is predicted to be only slightly greater than that of **1**, despite the fact that the double bond in cubene is much more highly pyramidalized. It is concluded that alkenes **10** and **1–3** provide an ideal series of molecules in which to study the effects of double-bond pyramidalization, uncomplicated by any contribution from the OSE present in the bicyclic reference compound.

We have recently reported the synthesis[1-3] and characterization[3,4] of three members (**1**, **2**, and **4**) of a homologous series of alkenes in which a short chain of *n* atoms, bridging between C-3 and C-7 of bicyclo[3.3.0]oct-1(5)-ene, forces the doubly bonded carbons to pyramidalize. The chemistry that we have observed

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[†] Dedicated to Professor E. J. Corey on the occasion of his 60th birthday.

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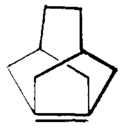
0002-7863/88/1510-4710$01.50/0 © 1988 American Chemical Society

is indicative of the presence of substantial strain in these olefins.

1



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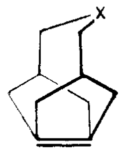
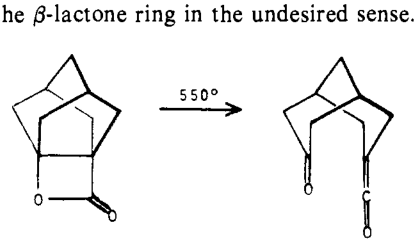


3, X = CH_2
4, X = $SeCH_3^+$

For example, the β-lactone precursor of the $n = 2$ alkene (**2**) exhibits unusual stability toward loss of CO_2 upon heating.[2] The $n = 1$ β-lactone (**5**) is even more resistant toward thermal decarboxylation.[1] On flash vacuum pyrolysis at 550 °C, it is only 50% decomposed. Moreover, the product at this temperature is not the $n = 1$ alkene (**1**) but, instead, keto ketene **6**, formed by cleavage of the β-lactone ring in the undesired sense.

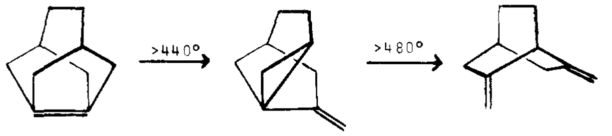


5 **6**

From the heats of formation of the products,[5] fragmentation of the parent 2-oxetanone to ethylene plus CO_2 is found to be enthalpically more favorable than cleavage to formaldehyde plus ketene by 39.3 kcal/mol. If the energies of the transition states for these two modes of β-lactone cleavage parallel the energies of the two sets of products, the observation that pyrolysis of **5** produces **6** instead of **1** is indicative of a strain energy in **1** of at least 40 kcal/mol more than that in **6**. In fact, since fragmentation of **5** to **1** plus CO_2 should be entropically more favorable than cleavage to **6**, the formation of **6** at 550° suggests that the strain energy of **1** may be well in excess of this lower limit.

Setting a lower limit of 40 kcal/mol for the strain in **1**, due to the presence of the pyramidalized double bond, involves the questionable assumption that the energy difference between the transition states for the two possible modes of β-lactone fragmentation is comparable to the energy difference between the products. In contrast, in **2** a lower limit to the strain due to the presence of the pyramidalized double bond can be obtained from an experiment in which an equilibrium is established, rather than one in which the relative rates of two different reactions are compared.

We have found that, upon pyrolysis, **2** rearranges to **7**.[6] This is the reverse of the usual vinylcyclopropane rearrangement, which leads to formation of cyclopentene.[7] Moreover, **7** is a strained vinylcyclopropane, since it may be viewed as a derivative of *trans*-bicyclo[5.1.0]octane.[8] In fact, at higher temperatures relief of strain in the trans-bridged cyclopropane ring of **7** causes this hydrocarbon to undergo isomerization to 2,6-dimethylenebicyclo[2.2.2]octane (**8**).[6]



2 **7** **8**

From the difference between the heats of formation of vinylcyclopropane and cyclopentene,[5] the exothermicity of the rearrangement of the former to the latter is 17.5 kcal/mol. Since the equilibrium between **2** and **7** lies in the opposite direction, the strain in **2**, relative to that in cyclopentene, must be at least 18 kcal/mol greater than the strain in **7**, relative to vinylcyclopropane.

The presence of the trans-bridged cyclopropane ring in **7** destabilizes it, relative to vinylcyclopropane. A minimum value of 9 kcal/mol for the extra strain energy in **7**, due to the presence of the trans-bridged cyclopropane ring, is provided by the enthalpy of isomerization of a derivative of *trans*-bicyclo[5.1.0]octane to its cis isomer.[8h] Thus, 27 kcal/mol represents a lower limit to the amount by which the presence of the pyramidalized double bond in **2** causes its strain energy to exceed that of cyclopentene.[6]

This difference has also been computed.[6] The olefin strain energy (OSE)[9] of cyclopentene—the amount by which its strain energy exceeds that of cyclopentane—is small and negative, amounting to −3.1 kcal/mol with the MM2 force field.[10] The OSE of **2** is 18.3 kcal/mol. The resulting value of 21.4 kcal/mol for the difference in OSEs is smaller than the experimentally determined lower bound.

A value for the OSE of **2** can also be obtained from the difference between the heat of hydrogenation of **2** and that of an appropriate reference compound. For the purpose of making this comparison, the tetrasubstituted double bond in bicyclo[3.3.0]oct-1(5)-ene (**9**) provides a better reference than the disubstituted double bond in cyclopentene. The MM2 OSE of −0.7 kcal/mol for **9** is close to that of −3.1 kcal/mol calculated for cyclopentene.[6]

The heat of hydrogenation of **2** has been calculated,[6] using Dewar's semiempirical MNDO method.[11] The value of 72.1 kcal/mol obtained is 46.9 kcal/mol greater than the heat of hydrogenation of 25.2 kcal/mol computed for the unbridged reference compound (**9**). Because 46.9 kcal/mol is larger than 27 kcal/mol—the experimental value for the minimum amount of strain energy that is attributable to the presence of the pyramidalized double bond in **2**—the MNDO value for the OSE of **2** appears to be in better qualitative agreement with experiment than the MM2 value. However, without the experimental value for the heat of hydrogenation of **2**, it is impossible to determine which of the two semiempirical methods actually provides the better quantitative estimate of the OSE in **2**.

Reliable values for the OSE in **2** and in the other members of this series of pyramidalized alkenes would be quite useful for interpreting and predicting their chemistry. For example, from the OSE for the as yet unknown $n = 3$ hydrocarbon (**3**), one could predict whether, like the $n = 2$ alkene (**2**), it too is likely to undergo a retrograde vinylcyclopropane rearrangement. Since only the geometry of the selenium-bridged derivative of $n = 3$ (**4**) has been established experimentally,[3] calculation of optimized geometries for the alkenes is also highly desirable. As might be expected from the larger OSE computed by MNDO for **1** and **2**, MNDO also predicts less double bond pyramidalization in these alkenes than MM2.[6]

In this paper we report the results of ab initio calculations of the optimized geometries of **1**–**3** and of their hydrogenation energies. These energies are compared to the hydrogenation energy computed for the unbridged alkene (**9**), in order to obtain the OSE

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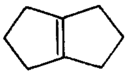
Table I. Ethylene[a] Pyramidalization Energies (kcal/mol) Calculated with 3-21G and DZP Basis Sets and SCF, TCSCF, and SD–CI Wave Functions

	3-21G			DZP		
ϕ[b]	SCF	TCSCF	SD–CI	SCF	TCSCF	SD–CI
0	-77.5998[c]	-77.6305[c]	-77.8004[c]	-78.0443[c]	-78.0725[c]	-78.3106[c]
18	5.6	4.4	4.6	5.3	4.1	4.3
36	22.5	18.6	18.8	21.1	17.4	17.5
54	52.0	44.5	44.4	48.2	41.4	40.9
72	98.0	87.5	85.9	89.1	79.9	77.9
90	168.9	157.5	152.8	150.9	141.8	136.6

[a] R_{C-C} = 1.338 Å, R_{C-H} = 1.086 Å, H–C–H = 117.6°. [b] Pyramidalization angle in degrees. [c] Reference energy in hartrees.

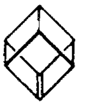
of **1–3**. In addition, we have computed the geometry and hydrogenation energy of the most strained member of this series of pyramidalized alkenes, the as yet unknown tricyclo[3.3.0.0^{3,7}]oct-1(5)-ene (**10**).



9

10

For comparison with this series of pyramidalized alkenes, in which the double bond is part of two five-membered rings, we have also optimized the geometry and computed the hydrogenation energy of cubene (**11**), in which the double bond is contained in two four-membered rings, and of tricyclo[3.1.0.0^{2,6}]hex-1(6)-ene (**12**),[12] wherein the double bond is part of two three-membered rings. As bicyclic references for these two, pyramidalized, polycyclic alkenes we have computed the heat of hydrogenation of bicyclo[2.2.0]hex-1(4)-ene (**13**)[13] and bicyclo[1.1.0]but-1(3)-ene (**14**). Wiberg and co-workers have previously reported calculations of the heats of hydrogenation of these two bicyclic alkenes.[14]



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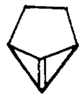

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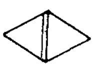

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Methodology

The accurate calculation of the heat of hydrogenation of an alkene requires that any errors in the C–C double bond and H–H single bond energies of the reactants be cancelled by errors in the C–C and C–H single bond energies of the product. Wiberg and co-workers have found that, when self-consistent field (SCF) calculations are performed with the 6-31G* basis set, and after correction for differences in zero-point energies and changes in heats of formation on going from 0 to 298 K, heats of hydrogenation of planar double bonds are overestimated by 6 ± 2 kcal/mol.[14] They attributed this error largely to differences in electron correlation between H–H and C–H bonds, which are not accounted for at the SCF level of theory.

We were much less interested in the absolute heats of hydrogenation of pyramidalized alkenes **1–3** and **10–12** than in their heats of hydrogenation relative to those of reference compounds **9**, **13**, and **14**. Because of the cancellation of errors expected when differences in heats of hydrogenation are computed, we only needed to ensure that the computational methodology used would provide accurate relative energies for planar and pyramidalized double bonds. In order to determine what level of theory would be required to accomplish this goal, we performed calculations on planar and pyramidalized ethylene.

Ab initio methodology has an advantage over semiempirical techniques like MM2 and MNDO. In calculations on molecules for which there are no experimental data, the quality of ab initio calculations can be systematically improved until convergence of the results is achieved. In order to establish at what level of theory convergence is reached in calculation of the pyramidalization energy of ethylene, we carried out calculations with three different basis sets. The basis sets used were the 3-21G split-valence (SV),[15] Dunning's double-ζ (DZ),[16] and Dunning's double-ζ augmented with a set of polarization functions on carbon (DZP).

At each pyramidalized geometry three different types of calculations were performed with each basis set. In addition to an SCF calculation, which provided for no correlation between electrons, a two-configuration SCF (TCSCF) calculation, which correlated the pair of electrons in the highest occupied MO (HOMO), was also carried out. Finally, a CI calculation, which correlated all of the valence electrons by including single and double excitations from the TCSCF wavefunction, was performed. In C_{2v} symmetry these SD–CI calculations involved 3008 spin-adapted configurations with the SV basis set and 11 834 with the DZP basis set. All of these calculations were performed with MELD.[17]

The calculations were carried out at geometries in which both carbons were pyramidalized in a syn fashion, and the bond lengths and H–C–H bond angles used for planar ethylene were not reoptimized.[18] Each geometry can thus be specified with a pyramidalization angle, ϕ, which is defined as the angle between the plane of each CH_2 group and the extension of the C–C bond. The results of the calculations on pyramidalized ethylene are given in Table I.

The results with the DZ basis set are not tabulated, because the energy increases on ethylene pyramidalization that were computed with this basis set were within 1.0 kcal/mol of the 3-21G results through ϕ = 72°. Although the SV basis performs about as well as a DZ basis set, from the tabulated results it is clear that the presence of polarization functions in the DZP basis set does reduce the computed pyramidalization energy. The reduction in the calculated pyramidalization energy on inclusion of polarization functions is largest at the SCF level.

Table I also shows that, for pyramidalization angles up to about 70°, provision of correlation for the electrons in the HOMO is even more important than the addition of polarization functions to the SV basis set. With both the SV and DZP basis sets, the TCSCF calculations give almost the same pyramidalization energies as the SD–CI calculations through ϕ = 54°; even at ϕ = 72° the TCSCF values are only about 2 kcal/mol greater than those obtained with SD–CI.

The data in Table I serve to establish that, for all but the most severely pyramidalized alkenes, TCSCF calculations should give

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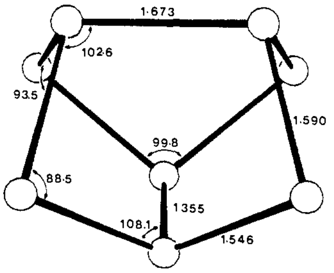

Figure 1. 3-21G SCF optimized geometry of **10**, bond lengths in angstroms, angles in degrees; ϕ = 61.2°.

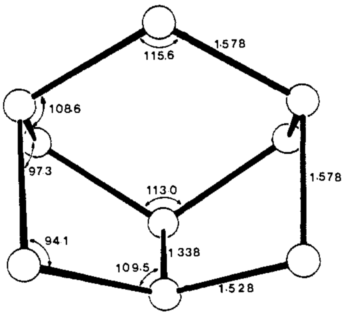

Figure 2. 3-21G SCF optimized geometry of **1**, bond lengths in angstroms, angles in degrees; ϕ = 52.8°.

adequate estimates of pyramidalization energies. Althouth it is clear that inclusion of polarization functions in the basis set is desirable, the SV basis set, which lacks polarization functions, overestimates the TCSCF pyramidalization energy by less than 10%. Obviously, the absolute error caused by using the SV basis set, instead of the DZP basis set, increases with the pyramidalization angle.

On the basis of the results contained in Table I, we would have liked to carry out all our calculations on pyramidalized alkenes, including the geometry optimizations, with a polarized basis set and a TCSCF wavefunction. However, some of the alkenes of interest to us were sufficiently large that we were only able to optimize their geometries at the SCF level of theory with the 3-21G basis set and to calculate their 6-31G* TCSCF energies at the 3-21G SCF optimized geometries. SCF geometry optimizations were performed with Gaussian 82,[19a] and TCSCF geometry optimizations were done with the GVB module in Gaussian 86.[19b]

The fact that a 3-21G SCF calculation gives too great an energy increase on double-bond pyramidalization will tend to introduce errors in the optimized geometry. A 3-21G SCF geometry optimization would be expected to underestimate the amount of double-bond pyramidalization and, consequently, to overestimate the strain built into other parts of the molecule. Nevertheless, when the geometries of some of the most highly pyramidalized alkenes were reoptimized with a TCSCF wavefunction, the energies calculated at the reoptimized geometries differed by, at most, a few kilocalories/mole from those obtained at the 3-21G SCF optimized geometries (vide infra).

Results and Discussion

Geometries. Shown in Figures 1–4 are the 3-21G SCF optimized geometries of the alkenes in the homologous series comprised of **10** and **1–3**. For comparison, the C_{2v} optimized geometry[20] of the unbridged reference compound (**9**) is given in Figure 5. The cartesian coordinates for the optimized geometries of the alkenes and the corresponding alkanes are available as supplementary material.[21]

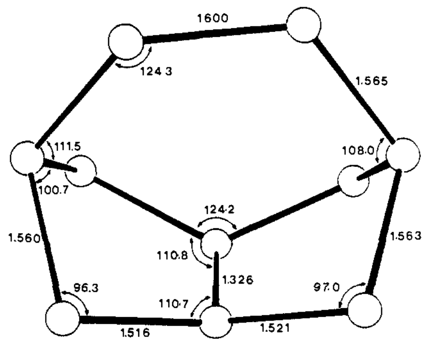

Figure 3. 3-21G SCF optimized geometry of **2**, bond lengths in angstroms, angles in degrees; ϕ = 40.8°.

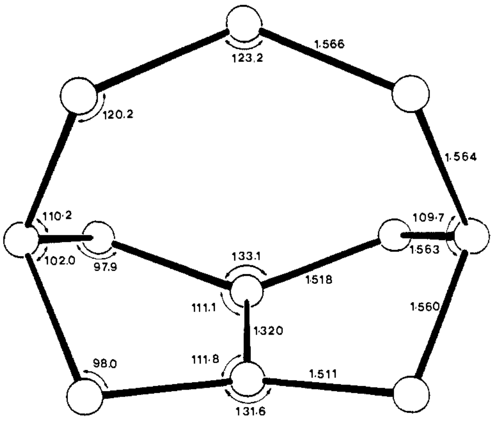

Figure 4. 3-21G SCF optimized geometry of **3**, bond lengths in angstroms, angles in degrees; ϕ = 25.0 and 25.2°.

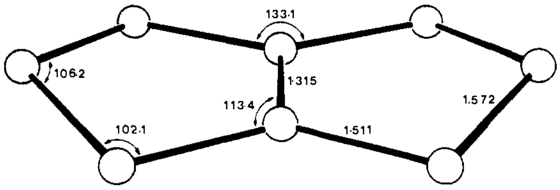

Figure 5. 3-21G SCF optimized geometry of **9**, bond lengths in angstroms, angles in degrees; ϕ = −3.6°.[24]

Several trends are apparent in the optimized geometries on moving along the series from **10** to **9**. As noted in the X-ray structure of **4**,[3] the five-membered rings try to accommodate themselves to the increasingly short chains of bridging methylene groups by puckering, thus decreasing the bond angles within the five-membered rings along the series. At the same time the bridging chain deforms to span the bicyclo[3.3.0]octene moiety. As in the case of **4**, the deformation involves some opening of the bond angles in the chain and lengthening of the bonds.

The length of the bridging bond in **10** is calculated to be 1.673 Å, which is reduced to 1.623 Å in the saturated hydrocarbon. A vibrational analysis showed that the C_{2v} geometry that was optimized is a true energy minimum for the $n = 0$ alkene (**10**).

In the $n = 1$ alkene (**1**) the bonds to the bridging methylene are 1.578-Å long, and the bond angle at this carbon is 115.6°. In the hydrogenation product of **1** this bond length is reduced to 1.553 Å and the bond angle to 112.0°.

Notable features of the optimized geometry[22] for the $n = 2$ alkene (**2**) are the large C–C–C bond angles at the two bridging carbons and the twisting of the ethano bridge. The twisting confers

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(19) (a) Binkley, J. S.; Frisch, M. J.; Raghavachari, M.; Fluder, E.; Seeger, R.; Pople, J. A. Carnegie-Mellon University. (b) Frisch, M. J.; Binkley, J. S.; Schlegel, H. B.; Raghavachari, K.; Martin, R.; Stewart, J. J. P.; Bobrowicz, F.; Defrees, D.; Seeger, R.; Whiteside, R.; Fox, D.; Fluder, E.; Pople, J. A. Carnegie-Mellon University.

(20) The optimized C_{2v} geometry of **9** was found to be lower in energy than the optimized C_{2h} geometry by 0.0003 hartree (0.2 kcal/mol). Each geometry was shown to be a true minimum by a full vibrational analysis.

(21) Ordering information is given on any masthead page.

(22) Although, at termination of the geometry optimization of **2**, the maximum force was twice that of the default value in Gaussian 82, the energy had decreased by less than 10^{-6} hartree for five consecutive steps.

Table II. Energies (Hartrees) Calculated at 3-21G SCF Optimized Geometries for Alkenes and Their Hydrogenation Products

	3-21G		6-31G*	
molecule	SCF	TCSCF	SCF	TCSCF
1	−345.7696	−345.8123[a]	−347.6863	−347.7272
1-H_2	−347.0547		−348.9694	
2	−384.6149	−384.6504		
2-H_2	−385.8670			
3	−423.4563	−423.4865	−425.8111	
3-H_2	−424.6720		−427.0258	
9	−308.1981	−308.2250	−309.9174	−309.9427
9-H_2	−309.3884		−311.1016	
10	−306.8577	−306.9107[b]	−308.5586	−308.6091
10-H_2	−308.1863		−309.8839	
11	−304.3859	−304.4319[c]	−306.0977	−306.1381
11-H_2	−305.6959		−307.3906	
12	−229.1401	−229.1900	−230.4704	−230.5122
12-H_2	−230.4736		−231.7775	
13	−230.4145	−230.4416	−231.7160	−231.7411
13-H_2	−231.6744		−232.9636	
14	−152.6662	−152.7134	−153.5773	−153.6172
14-H_2	−153.9866		−154.8696	

[a] At the TCSCF optimized geometry, the TCSCF energy is −345.8150 hartrees. [b] At the TCSCF optimized geometry, the TCSCF energy is −306.9152 hartrees. [c] At the TCSCF optimized geometry, the TCSCF energy is −304.4348 hartrees.

C_2 symmetry on the molecule and results in a small amount of torsion in the double bond. A symmetry lower than C_{2v} for **2** has been established experimentally by the polarized IR spectrum of the matrix isolated molecule.[4]

Molecular models of **2** indicate that, in order to accomodate a C_{2v} geometry, the C–C–C bond angles at the two bridging carbons would have to be even larger than the 124.3° calculated for the optimized C_2 structure. Twisting of the ethano bridge alleviates part of this problem, although the C–C–C bond angles remain much larger than tetrahedral. This problem is not unique to the alkene; for the optimized geometry of its hydrogenation product, tricyclo[3.3.2.$0^{3,7}$]decane, also has a twisted ethano bridge and C–C–C bond angles at the bridging carbons of 120.3°.

The optimized geometry of **3** contains many of the same features found experimentally in the X-ray structure of a salt of the 10-selena derivative (**4**).[3] As a consequence of the smaller bond length and larger bond angle of carbon compared to selenium, all of the calculated bond angles in the three-atom bridge of **3** are larger than those found experimentally in the three-atom bridge of selenonium salt **4**. Saturation of the double bond in **3** reduces the calculated central C–C–C bond angle in the three-atom bridge from 123.2° to 118.0°.

The replacement of the two Se–C bonds in the three-atom bridge of **4** with shorter C–C bonds in **3** results in an increase in the pyramidalization of the doubly bonded carbons. The pyramidalization angles of 25.0° and 25.2° calculated in **3** are both larger than those of 12.3° and 20.3° found in selenonium salt **4**. The larger of the two pyramidalization angles is syn to the three-atom bridge in **3**;[23] whereas, in **4** the larger angle is at the carbon anti to this bridge.

Pyramidalization occurs at the doubly bonded carbon atoms in order to decrease the angle between the mean planes of the two five-membered rings. Decreasing this angle results in a decrease in the angle between the bonds connecting each doubly bonded carbon and the two allylic carbons attached to it. This bond angle decreases from 133.1° in **9** to 99.8° in **10**. This decrease results in an increase in the computed pyramidalization angle, ϕ, from −3.6°[24] in **9** to 61.2° in **10**.

Table III. 3-21G SCF Orbital Energies (kcal/mol) of the HOMO and LUMO of Alkenes **1–3** and **10**, Relative to the Energies of the HOMO and LUMO of **9**

alkene	ϵ (HOMO)	ϵ (LUMO)
9	0[a]	0[b]
3	5.6	−18.2
2	7.5	−31.8
1	10.1 (15.0)[c]	−47.0 (−57.8)[c]
10	6.4 (14.0)[c]	−67.1 (−80.7)[c]

[a] ϵ = −8.60 eV. [b] ϵ = 5.65 eV. [c] Computed at the TCSCF optimized geometry.

For reference, it should be noted that the pyramidalization angle at a carbon with tetrahedral bond angles is 54.7°. Indeed, the bond angles at the doubly bonded carbon in **1**, which has ϕ = 52.8°, are close to tetrahedral. Rehybridization of the doubly bonded carbons on going from nearly planar in **9** to highly pyramidal in **10** is probably at least partly responsible for the increase in the lengths of all the bonds to these carbons along the series.

The 3-21G SCF energies of the alkenes and alkanes are given in Table II, and the TCSCF energies of the alkenes, computed at the optimized SCF geometries are also listed. The SCF orbital energies of the HOMO and LUMO of each alkene, relative to the HOMO and LUMO energies of unbridged olefin **9**, are given in Table III.

HOMO and LUMO Energies. The HOMO and LUMO energies are of interest because the $n = 2$ alkene (**2**) shows a long wavelength UV absorption with a maximum around 245 nm.[4] The bathochromic shift on going from **9**, which shows no long wavelength absorption, to **2** could be due either to an increase in the HOMO energy, a decrease in the LUMO energy, or a combination of both. The orbital energies in Table III show that there is only a small increase in the calculated energy of the HOMO on pyramidalization, which reaches a maximum at **1** and then decreases slightly on going from **1** to the still more highly pyramidalized **10**. In contrast, there is a large, monotonic decrease in the calculated energy of the LUMO with increasing amounts of pyramidalization.

It would be of considerable interest to have the experimental values for the ionization potentials and electron affinities of these alkenes, in order to test the predicted behavior of the HOMO and LUMO energies.[26] Nevertheless, although the very small increase predicted for the HOMO energy at first may seem surprising, especially in view of the large monotonic decrease predicted for the LUMO energy, these orbital energy changes are readily explained.

On pyramidalization of the doubly bonded carbons, two effects are expected as a result of the hybridization of the 2p atomic orbitals that constitute the HOMO and LUMO. As the 2p orbitals become hybridized, their overlap decreases. This probably accounts for some of the lengthening of the bond between these carbons along the series on going from **9** to **10**. The decrease in overlap between the AO's raises the energy of the HOMO, but, because the AO's in the LUMO are out of phase, its energy is lowered, and the magnitude of the change in its energy is greater than that in the HOMO.

In addition, as the 2p π AO's acquire 2s character on pyramidalization, the energy of the hybrid AO's decreases, since 2s

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[23] MM2 predicts the larger of the pyramidalization angles in **3** also to be syn to the three-atom bridge, not anti, as stated erroneously in ref 3. The fact that the anti carbon of the double bond in salt **4** is found experimentally to be significantly more pyramidal than the syn carbon may be due to an attraction between the positively charged selenonium center and the π electrons of the double bond. Such an attractive interaction would tend to flatten the doubly bonded carbon that is syn to the selenonium ion.

[24] The negative sign is due to the fact that in **9** pyramidalization of the olefinic carbons occurs so that the single bonds are pyramidalized anti to the apical carbons of the two five-membered rings, rather than syn, as in **1–3** and **10**. The reason for anti pyramidalization in **9** is obviously related to the similar mode of pyramidalization of the double bond in norbornene and in related compounds.[25] It should be noted that the C_{2v} geometry of **9**, which allows pyramidalization of the double bond, is slightly lower in energy than the C_{2h} geometry,[20] which does not permit pyramidalization. This finding is consistent with Houk's argument that pyramidalization results in a reduction of eclipsing energy.[25]

[25] Review: Houk, K. N.; Rondan, N. G.; Brown, F. K. *Isr. J. Chem.* **1983**, *23*, 3.

[26] Lowering of the LUMO and a much smaller increase in the energy of the HOMO has previously been noted in calculations on trans bent acetylene and anti pyramidalized ethylene by Stozier, R. W.; Caramella, P.; Houk, K. N. *J. Am. Chem. Soc.* **1979**, *01*, 1340.

Table IV. Olefin Strain Energies (kcal/mol) Computed as the Difference between the Hydrogenation Energy of Each Alkene and That of **9**

	3-21G		6-31G*			
alkene	SCF	TCSCF	SCF	TCSCF	MM2	MNDO
9	0	0	0	0	−0.7	0
3	16.0	13.9	19.2	17.7[a]	9.8	30.8
2	38.8	33.3	41.7[b]	37.4[a]	18.2	46.9
1	59.5	49.5[c]	62.1	52.3	24.5	66.6
10	86.8	70.4[d]	88.6	72.8	29.9	91.9
11	75.1	63.1[e]	68.2	58.9		
13	43.7	43.5	39.8	40.0		
12	89.9	75.4	77.1	66.8		
14	81.7	68.9	67.9	58.7		

[a] TCSCF OSE estimated by using the SCF energy and the data in Table V. [b] Estimated by interpolating between the changes in the SCF OSEs for **1** and **3** on going from 3-21G to 6-31G*. [c] 47.8 kcal/mol by using the TCSCF energy at the TCSCF optimized geometry. [d] 67.6 kcal/mol by using the TCSCF energy at the TCSCF optimized geometry. [e] 61.4 kcal/mol by using the TCSCF energy at the TCSCF optimized geometry.

orbitals are lower in energy than 2p orbitals. This effect stabilizes both the HOMO and the LUMO. In the case of the HOMO, this latter effect works in the opposite direction from the decreased overlap between the AO's, thus accounting for the calculated behavior of the HOMO energies. In the case of the LUMO, the two effects are additive, thus explaining the large monotonic decrease in the computed LUMO energies on going along the series from **9** to **10**.

Olefin Strain Energies (OSEs). From the difference in Table II between the energy of each of the alkenes and the saturated hydrocarbon derived from it, we have computed the OSE of each alkene by subtracting the calculated energy difference between **9** and bicyclo[3.3.0]octane. Values for the OSEs, computed from both the SCF and TCSCF energies, are given in Table IV.

The effect of performing TCSCF geometry optimizations was investigated for **10** and **1**. As expected, for **10** the TCSCF optimized double bond length of 1.434 Å is substantially longer than the SCF bond length of 1.355 Å; at the TCSCF optimized geometry, the 3-21G TCSCF energy of **10** is 2.8 kcal/mol lower than at the SCF optimized geometry. For the less highly pyramidalized homologue, **1**, the TCSCF and SCF optimized double bond lengths of respectively 1.389 and 1.338 Å are closer, and the 3-21G TCSCF energy difference between the two geometries is only 1.7 kcal/mol. However, even for **10**, the most strained member of this homologous series of pyramidalized alkenes, geometry optimization at the TCSCF level of theory reduces the computed OSE by less than 4%.

With the bond angles and C–C bond lengths obtained from the optimized SCF geometries for **10**, **1–3**, and **9**, another set of calculations on pyramidalized ethylene was performed. The results are listed in Table V.

The difference between the 3-21G SCF and TCSCF OSE for each alkene in Table IV is close to the difference between the appropriate 3-21G SCF and TCSCF ethylene pyramidalization energy in Table V. The largest discrepancy between the two tables occurs for **10**, where the difference of 16.4 kcal/mol between the SCF and TCSCF values for the OSE in Table IV is 1.4 kcal/mol larger than the difference between the 3-21G SCF and TCSCF values in Table V for the energy required to pyramidalize ethylene from the geometry of **9** to that of **10**.

In order to test the prediction of Table V that only a small lowering in the OSE, computed for even the most strained members of this series, should result from inclusion of polarization functions in the basis set, we recalculated the energies of **10**, **1**, **3**, **9**, and the hydrogenation product of each of these alkenes with the 6-31G* basis set.[27] The 6-31G* calculations were performed at the 3-21G optimized geometry of each hydrocarbon. The 6-31G* SCF and TCSCF energies are given in Table II, and the derived OSEs for **10**, **3**, and **1** are listed in Table IV.

In contrast to what one would have expected from the ethylene pyramidalization energies in Table V, the OSEs calculated for **10**, **3**, and **1** actually increase on going from 3-21G to 6-31G*. For example, the 6-31G* SCF OSE of **3** is 19.2 kcal/mol; whereas, from the 3-21G SCF value in Table IV and the difference between the 3-21G and DZP SCF ethylene pyramidalization energies in Table V, a 6-31G* SCF OSE of 15.2 kcal/mol would have been expected. The discrepancy between the calculated and anticipated 6-31G* SCF OSEs for **1** and **10** is even larger, amounting to 5.4 kcal/mol for each alkene.

It seems likely that the polarization functions on carbon in the 6-31G* basis set improve the description of C–H hyperconjugation with the π bond at the nearly planar equilibrium geometry of **9**. Since C–H hyperconjugation is reduced upon double bond pyramidalization, this would account for the increase in the computed OSEs on going from 3-21G to 6-31G*. Consistent with this explanation is the finding that hydrogenation of **9** is computed to be 6.2 kcal/mol less exothermic with 6-31G* than with 3-21G (vide infra).

With the 6-31G* basis set, as with 3-21G, the reduction in the calculated OSEs on going from SCF to TCSCF wave functions for **10** and **1** can be predicted rather well from the difference between the SCF and TCSCF pyramidalization energies in Table V. Thus, we are confident in using the data in Table V to estimate the 6-31G* TCSCF OSE of **3**, which is given in Table IV.

From the changes in the SCF OSEs for **3** and **1** on going from 3-21G to 6-31G*, the expected change in the SCF OSE for **2** can be obtained by interpolation. The resulting estimate of the 6-31G* SCF OSE for **2** is given in Table IV. The 6-31G* TCSCF value for the OSE of **2**, which is also given in Table IV, was obtained from the SCF value and the data in Table V.

The OSEs for alkenes **1–3** and **10**, calculated by MM2 and obtained from the MNDO heats of hydrogenation, are also given in Table IV.[28] From the tabulated results, it appears that the MM2 potential for double-bond pyramidalization is much too soft. Houk and co-workers have previously come to the same conclusion.[29] In contrast to the MM2 values for the OSE, which are too small, the MNDO values appear too large.

Since the MNDO calculations do not take into account the increasing importance of electron correlation in the HOMO on pyramidalization, the MNDO values for the OSEs should really be compared with the SCF values, rather than with the TCSCF numbers. As shown in Table IV, the MNDO OSEs exceed the 6-31G* SCF values by between 3 and 5 kcal/mol, except for **3** where the difference is more than 10 kcal/mol.

The 6-31G* TCSCF OSEs for **1** and **2** in Table IV are large enough to accommodate the experimental data that exists on these alkenes. For example, the calculated OSE of **1** is well above the roughly 40 kcal/mol necessary to ensure that **5**, the β-lactone precursor of **1**, should prefer enthalpically to cleave to ketoketene **6**, rather than to lose CO_2 to generate **1**. Similarly, the OSE computed for **2** is larger than 27 kcal/mol, which we estimate is the minimum necessary to make the rearrangement of **2** to **7** thermodynamically favorable.

From the OSEs in Table IV one can also make predictions about **3** and **10**, the as yet unknown members of this series. The 6-31G* TCSCF OSE of **3** is estimated to be 17.7 kcal/mol, which is slightly more than the 17.5 kcal/mol required to make a retrograde vinylcyclopropane rearrangement enthalpically favorable. However, the product of the retrograde vinylcyclopropane rearrangement of **3** would contain a *trans*-bicyclo[6.1.0]nonane moiety with an sp^2 center in the six-atom bridge, which should introduce about 3 kcal/mol of additional strain into the rearrangement product.[30] Thus, we predict that, unlike the case with **1** and **2**,

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(27) Hariharan, P. C.; Pople, J. A. *Theor. Chim. Acta* **1973**, *38*, 213.

(28) The MM2 numbers were taken from the Ph.D. Thesis of Renzoni, G. E.; University of Washington, 1984. The MNDO numbers were calculated by Downing, J. W. and Michl, J., whom we thank for communicating their results to us. Some of these numbers have been published previously.[6]

(29) Houk, K. N.; Rondan, N. G.; Brown, F. K.; Jorgensen, W. L.; Madura, J. D.; Spellmeyer, D. C. *J. Am. Chem. Soc.* **1983**, *105*, 5980.

(30) Wiberg, K. B.; Lupton, E. C., Jr.; Wasserman, D. J.; de Meijere, A.; Kass, S. R. *J. Am. Chem. Soc.* **1984**, *106*, 1740.

Table V. Relative Energies (kcal/mol) of Ethylene[a] at Geometries Corresponding to Those in **1**–**3**, **9**, and **10**

	3-21G			DZP		
geometry	SCF	TCSCF	SD-CI	SCF	TCSCF	SD-CI
9	−77.5828[b]	−77.6120[b]	−77.7817[b]	−78.0280[b]	−78.0547[b]	−78.2938[b]
3	9.1	7.7	7.4	8.3	6.8	6.7
2	20.1	15.6	15.5	18.3	14.0	14.3
1	40.1	31.1	31.0	37.3	28.9	29.5
10	71.3	56.3	56.0	67.7	53.8	54.4

[a] R_{C-H} fixed at 1.086 Å. [b] Reference energy in hartrees.

a retrograde vinylcyclopropane rearrangement of **3** will probably prove enthalpically unfavorable, though only by a very small amount.[31]

In **10**, the most highly pyramidalized member of the series, the calculated 6-31G* TCSCF OSE of 72.8 kcal/mol exceeds the experimental π bond energy of ethylene of 65 kcal/mol.[32] It should be noted, however, that there is still a strong "π" bond in **10**, as evidenced by both the calculated length of the double bond (1.355 Å at the SCF level and 1.434 Å at the TCSCF level) and by the ratio of 5.3 for the squares of the two coefficients in the TCSCF wavefunction at the TCSCF optimized geometry. Were there no "π" bond in **10**, a significantly longer C–C bond length would be expected, and the squares of the two coefficients would be identical. Nevertheless, despite this evidence for the existence of a "π" bond in **10**, its very large OSE should make it extraordinarily susceptible to double bond addition reactions.

Heats of Hydrogenation. With a value for the heat of hydrogenation of **9**, the data in Table IV can be used to predict the heats of hydrogenation of the other alkenes in this table. The SCF energy of H_2 is −1.1230 hartree with the 3-21G basis set and −1.1268 hartree with 6-31G*. Combining these numbers with the energies in Table II for **9** and for its hydrogenation product gives −42.2 kcal/mol as the energy of hydrogenation with the 3-21G basis set and −36.0 kcal/mol with 6-31G*.

In order to obtain the heat of hydrogenation at room temperature, the hydrogenation energy must be corrected for the difference in zero-point energies between reactants and products and for the changes in their heats of formation on going from 0 to 298 K. Use of values of 8.2 and −1.8 kcal/mol, respectively, for these two corrections[14] gives a calculated enthalpy change on hydrogenation of **9** at room temperature of −35.8 kcal/mol with 3-21G and −29.6 kcal/mol with 6-31G*.

As discussed in the section on methodology, differences in electron-correlation energies between reactants and product result in SCF heats of hydrogenation that contain larger errors than relative heats of hydrogenation calculated at the same level of theory. With the 6-31G* basis set, Wiberg and co-workers found that the SCF heats of hydrogenation were overestimated by 6 ± 2 kcal/mol.[14] Where comparisons are available,[33] similar errors in heats of hydrogenation appear to result from SCF calculations with the 3-21G basis set. Thus, we predict a heat of hydrogenation for **9** of 29.8 ± 2 kcal/mol with 3-21G and 23.6 ± 2 kcal/mol with 6-31G*.

A check on the reliability of the heat of hydrogenation predicted for **9** is provided by comparison of the heat of hydrogenation predicted for cyclopentene with the experimental value.[34] We calculated the 3-21G SCF energies of cyclopentene and cyclopentane to be, respectively, −192.9020 hartrees and −194.0885 hartrees, giving a calculated energy change on hydrogenation of −39.8 kcal/mol. After correction for zero-point energy differences and differences between heats of formation at 0 and 298 K,[14] the heat of hydrogenation of cyclopentene is calculated to be 34.6 kcal/mol. The 6-31G* value is 30.7 kcal/mol.[14] Applying Wiberg's empirical correction of 6 ± 2 kcal/mol to both numbers, they become 28.6 ± 2 kcal/mol and 24.7 ± 2 kcal/mol. The experimental value of 26.7 kcal/mol[34] is midway between the two theoretical estimates and in satisfactory agreement with both of them.

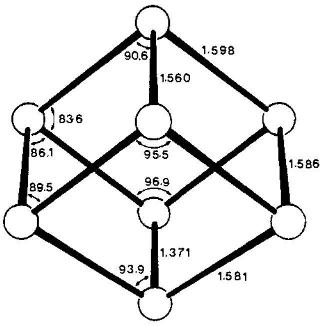

Figure 6. 3-21G SCF optimized geometry of **11**, bond lengths in angstroms, angles in degrees; ϕ = 84.1°.

Using the 6-31G* estimated heat of hydrogenation of **9** and the 6-31G* TCSCF OSE of **10** in Table IV, the heat of hydrogenation of the most strained member of this series of pyramidalized alkenes is predicted to be 96.4 kcal/mol. The heat of hydrogenation of **1**, the most strained alkene that we have succeeded in preparing to date, is calculated to be 75.9 kcal/mol.

Cubene (11). For comparison with the heats of hydrogenation of **10** and **1**, in which the pyramidalized double bond is contained in two five-membered rings, we also computed the heats of hydrogenation of cubene (**11**), in which the double bond is contained in two four-membered rings, and of tricyclo[3.1.0.0^{2,6}]hex-1(6)-ene (**12**), in which the pyramidalized double bond is contained in two three-membered rings. Cubene is as yet unknown, but its synthesis is currently being attempted.[35] Szeimies and co-workers have obtained evidence for the formation of **12**.[12]

In order to determine the effect of electron correlation on the geometry of cubene, we performed both SCF and TCSCF geometry optimizations with the 3-21G basis set. As expected, the largest change was a lengthening of the C–C double bond from 1.371 Å at the SCF level to 1.424 Å at the TCSCF level of theory. The TCSCF energy of −304.4348 hartress, which was computed at the TCSCF optimized geometry, is 1.8 kcal/mol lower than the TCSCF energy at the SCF optimized geometry.

The 3-21G SCF geometry of cubene is shown in Figure 6. A vibrational analysis confirmed that it is an energy minimum. The SCF and TCSCF energies at this geometry, calculated with both the 3-21G and 6-31G* basis sets, are given in Table II.

The SCF geometry of cubane was also optimized with the 3-21G basis set. The geometry is given as supplementary material and differed insignificantly from that obtained by previous geometry optimizations with other basis sets.[36] The 3-21G and 6-31G* SCF energies that were calculated at this geometry are given in Table II.[37]

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(31) A direct comparison of the energies calculated for **3** and its rearrangement product would provide a check on this prediction. However, the rearrangement product possesses no element of symmetry, making the necessary calculations considerably larger than those performed on **3**, which were carried out in C_s symmetry. The 6-31G* SCF calculation on **3** consumed approximately 4 h of CPU time on the Cray XMP/48 computer at SDSC.

(32) Based on the activation energy for interconversion of *cis*- and *trans*-1,2-dideuterioethylene: Douglas, J. E.; Rabinovitch, B. S.; Looney, F. S. *J. Chem. Phys.* **1955**, *23*, 315.

(33) *Carnegie-Mellon Quantum Chemistry Archive*, 3rd ed.; Whiteside, R. A., Frisch, M. J., Pople, J. A., Eds.; Carnegie-Mellon University: 1983.

(34) Roth, W. R.; Klarner, F. G.; Lennartz, H.-W. *Chem. Ber.* **1980**, *113*, 1818.

(35) Eaton, P. E.; private communication. We are attempting to prepare a homologue of **11**.

(36) Schulman, J. M.; Disch, R. L. *J. Am. Chem. Soc.* **1984**, *106*, 1202.

The OSE of cubene (**11**), calculated as the difference between its hydrogenation energy and that of **9**, is given at various levels of theory in Table IV. At all levels of theory the OSE of cubene is computed to be less than that of **10**. This is surprising, since the bond angles at the olefinic carbons in **11** are significantly more distorted than those in **10**, causing the pyramidalization angle of 84.1° in **11** to exceed that in **10** by 22.9°.

In fact, with the 6-31G* basis set the OSE computed for cubene (**11**) is closer to the OSE of **1** than to that of **10**. With this basis set, the OSE calculated for **11** exceeds that of **1** by 6.1 kcal/mol at the SCF and 6.6 kcal/mol at the TCSCF level of theory. Since **1** has been generated by reductive deiodination,[1] the fact that the OSE computed for cubene is comparable to that of **1** augurs favorably for the successful preparation of cubene by a similar route.

Cubene (**11**) contains a bicyclo[2.2.0]hex-1(4)-ene moiety. The latter alkene (**13**) has been prepared by Wiberg's group.[13] It has a high OSE, as revealed not only by its chemical reactivity[13] but also by its calculated heat of hydrogenation.[14] With the 6-31G* basis set Wiberg and co-workers computed the heat of hydrogenation of **13** to be 69.0 kcal/mol, after a 6.4 kcal/mol correction for zero-point energy and temperature effects. An additional empirical correction of 6 kcal/mol to account for correlation effect differences, which are neglected at the SCF level, gave an estimated heat of hydrogenation of 63 kcal/mol and an OSE of 35 kcal/mol.

We optimized the geometry of **13** and of its hydrogenation product with 3-21G SCF calculations. The optimized geometries were very close to those obtained by Wiberg and co-workers with the 4-31G basis set.[14] The energies calculated at the 3-21G geometries with both the 3-21G and 6-31G* basis sets are given in Table II, and the OSEs derived from them are listed in Table IV.

With the 3-21G basis set, the OSE of **13** is found to be 43.7 kcal/mol at the SCF and 43.5 kcal/mol at the TCSCF level of theory. Since **13** is planar and the geometry about the double bond in **9** is nearly so, the agreement between the SCF and TCSCF results is not surprising. Inclusion of polarization functions in the basis set reduces the calculated OSE of **13** to 39.8 kcal/mol at the SCF level of theory, which, again, is very close to the TCSCF value of 40.0 kcal/mol. Our 6-31G* estimate of the OSE of **13** is higher than that of Wiberg and co-workers[14] because of our use of the calculated heat of hydrogenation of 23.6 kcal/mol for **9** as the reference for an unstrained alkene.

The OSE of **11** is higher than that of **13** by about 19 kcal/mol at the TCSCF level with both basis sets. Since **11** is highly pyramidalized and **13** is planar, the substantial reduction in the calculated difference between their OSEs on going from the SCF to the TCSCF levels of theory is understandable; the latter is expected to be the more reliable. Thus, our calculations predict that the pyramidalization of the bicyclo[2.2.0]hex-1(4)-ene moiety in cubene contributes less than 20 kcal/mol to the OSE of this alkene. The major part of the OSE in **11** (68% at the 6-31G* TCSCF level of theory) is already present in the planar double bond of **13**.

As measured by the computed OSEs in Table IV, pyramidalization of the double bond in bicyclo[2.2.0]hex-1(4)-ene (**13**) to the geometry of cubene (**11**) is far easier than pyramidalization of the double bond in bicyclo[3.3.0]oct-1(5)-ene (**9**) to the geometry of **10**, **1**, or **2**. In fact, the 18.8 kcal/mol increase in the 6-31G* TCSCF OSE on going from **13** to **11** is only about 1 kcal/mol more than the increase on going from **9** to **3**. This is the case despite the much more highly pyramidalized geometry of cubene (ϕ = 84°) compared to that of **3** (ϕ = 25°).

The ease of pyramidalization of the doubly bonded carbons in **13** has been previously noted by Wagner et al.[38] The mixing between the strained σ bonds of **13** and the π orbital that occurs on pyramidalization makes this type of distortion much easier in **13** than in an alkene like **9** with relatively unstrained σ bonds.[39] In **14**, where the σ skeleton is even more strained, pyramidalization is actually predicted to be energetically favorable.[14,38,40] The flap angle between the two three-membered rings in **14** has been computed to be in the range 132–135°[14,38,40] and ϕ = 39.8°[41] at the 3-21G SCF optimized equilibrium geometry.

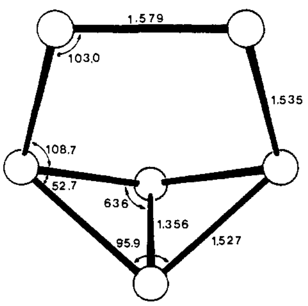

Figure 7. 3-21G SCF optimized geometry of **12**, bond lengths in angstroms, angles in degrees; ϕ = 48.4°.[42]

Tricyclo[3.1.0.0^{2,6}]hex-1(6)-ene (12). As a consequence of the pyramidalized equilibrium geometry of **14**, the additional strain, introduced by the constraints of the ethano bridge that is present in **12**, is minimal. The geometry of **12**, optimized by 3-21G SCF calculations, is shown in Figure 7.[42] The flap angle is reduced to 112°, and ϕ is increased to 48.4°. Nevertheless, the heat of hydrogenation of **12** is computed to be greater than that of **14** by only 8.2 kcal/mol at the SCF level and 6.5 kcal/mol at the TCSCF level with the 3-21G basis set. With the 6-31G* basis set, the SCF and TCSCF differences in heats of hydrogenation of **12** and **14** are respectively 9.2 and 8.1 kcal/mol.

Bicyclo[1.1.0]but-1(3)-ene (**14**) is a very strained alkene. From the results of their 6-31G* SCF calculations, Wiberg et al. estimated the heat of hydrogenation of **14** to be 90 kcal/mol, giving a value of 62 kcal/mol for the OSE in **14**.[14] Once again, our 6-31G* SCF value in Table IV is slightly higher, because of our use of the heat of hydrogenation of **9** as the reference.

Since **14** is quite pyramidalized, it is important to use a two-configuration wave function to describe the "π" bond in it.[40] As shown in Table IV, there is a substantial reduction in the calculated OSE of **14** on going from an SCF to a TCSCF wave function. The 6-31G* TCSCF value of 58.7 kcal/mol for the OSE of **14** is 9.2 kcal/mol less than the 6-31G* SCF value.

Even with a value of 58.7 kcal/mol for the OSE of **14**, the addition of the ethano bridge in **12** results in less than a 14% increment in the OSE. On distorting the double bond in bicyclo[2.2.0]hex-1(4)-ene (**13**) to the highly pyramidalized geometry of the double bond in cubene (**11**), the percentage increase (47%) in the OSE is larger. However, the major part of the OSE in cubene, too, is present at the planar equilibrium geometry of **13**.

Conclusions

Our computational results suggest the usefulness of dividing the OSE of a pyramidalized alkene into two contributions. One contribution comes from the OSE present in the unconstrained

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(37) The 6-31G* SCF energy of −307.3938 hartrees for cubane, reported by Schulman and Disch,[36] is 3.2 millihartrees below the energy given in Table II, because our calculation was performed at the 3-21G, rather than at the 6-31G*, optimized geometry.

(38) Wagner, H.-U.; Szeimies, G.; Chandrasekhar, J.; Schleyer, P. v. R.; Pople, J. A.; Binkley, J. S. *J. Am. Chem. Soc.* **1978**, *100*, 1210.

(39) Contrary to the impression that might be obtained from ref 38, mixing of the $3a_g$ MO of planar ethylene with the π MO ($1b_{2u}$) is not stabilizing, since both MO's are filled. The stabilization on ethylene pyramidalization comes from the mixing between $1b_{2u}$ and the unoccupied $4a_g$ MO.

(40) Hess, B. A., Jr.; Allen, W. D.; Michalska, D.; Schaad, L. J.; Schaefer, H. F., III *J. Am. Chem. Soc.* **1987**, *109*, 1615.

(41) In molecules like **12** and **14**, where all three atoms attached to each doubly bonded carbon lie in the same hemisphere, the double bond, rather than its extension, should be used to define the pyramidalization angle.

(42) After this manuscript was submitted, the geometry of **12**, optimized at various levels of theory, was published by Hess, B. A., Jr.; Michalska, D.; Schaad, L. J. *J. Am. Chem. Soc.* **1987**, *109*, 7546. Their 3-21G SCF optimized geometry is the same as the one depicted in Figure 7. As in the case of **14**,[40] they found that a vibrational analysis at the SCF level shows one negative force constant for the optimized C_{2v} geometry of **12**, but at the MP2 level of theory the C_{2v} geometry is a true minimum.

skeleton of the bicyclic reference olefin; the other comes from pyramidalization of the double bond in this skeleton. The olefin pyramidalization strain energy (OPSE) is the difference between the OSE of a pyramidalized alkene and that of the appropriate bicyclic reference compound.

In cubene (**11**) the majority of the calculated OSE is contained in bicyclo[2.2.0]hex-1(4)-ene (**13**). The 6-31G* TCSCF OPSE of 18.9 kcal/mol amounts to only 32% of the total OSE of 58.9 kcal/mol that is calculated for **11**. In **12**, of the computed OSE of 66.8 kcal/mol, the OPSE of 8.1 kcal/mol[43] amounts to just 12%. Thus, despite the fact that the large OSE predicted for **11** and **12** should confer on these molecules a high reactivity toward double-bond addition, most of the reactivity is expected to be found in the unbridged bicyclic alkenes **13** and **14**.

In contrast, MM2 predicts essentially no OSE for bicyclo[3.3.0]oct-1(5)-ene (**9**), and the 6-31G* heat of hydrogenation of 23.6 kcal/mol that we estimate for **9** is nearly the same as that computed for cyclopentene. Since the OSE of **9** is zero, or close to it, the OPSEs for **10** and **1–3** are the same as the OSEs for these alkenes, which are given in Table IV. The unusual physical and chemical properties of these molecules can, therefore, be attributed entirely to pyramidalization of the doubly bonded carbons in them. Consequently, this series of alkenes provides an excellent opportunity to study the spectroscopic and chemical consequences of olefin pyramidalization, without a significant contribution from the OSE present in the unconstrained bicyclic alkene.

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Note Added in Proof. The prediction that cubene (**11**) should be preparable by the same type of reaction used for the synthesis of **1**[1] has been confirmed. Cubene has been synthesized by reductive dehalogenation by M. Maggini and P. F. Eaton (submitted for publication in *J. Am. Chem. Soc.*) and we have generated homocub-4(5)-ene in the same fashion (submitted for publication in *J. Am. Chem. Soc.*).

Supplementary Material Available: Cartesian coordinates for the 3-21G SCF optimized geometries of alkenes **1–3** and **9–14** and of the hydrogenation product of each alkene (14 pages). Ordering information is given on any masthead page.

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[43] An alternative definition of the OPSE would involve planar bicyclic alkenes as reference molecules. Since **14** has been computed to have a 12 kcal/mol barrier to planarity,[41] this definition would confer on **12** a small negative OPSE, amounting to −4 kcal/mol.

The Three-Component Coupling Synthesis of Prostaglandins[†,1]

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Abstract: A convergent one-pot construction of the prostaglandin (PG) framework has been accomplished by the organocopper-mediated conjugate addition of the *S* configurated ω side-chain unit to a protected (*R*)-4-hydroxy-2-cyclopentenone followed by trapping of the enolate intermediate by α side-chain alkyl halides. Transmetalation with use of triphenyltin chloride at the enolate stage serves as key operation for the successful three-component coupling synthesis. The use of methyl (*Z*)-7-iodo-5-heptenoate as the α side-chain component allows short synthesis of PGE$_2$ and PGD$_2$. Introduction of a triple bond at the C-5–C-6 positions with methyl 7-iodo-5-heptynoate as the α side-chain synthon has opened a general entry of PGs. The protected 5,6-didehydro-PGE$_2$ derivatives are convertible to a variety of PGs of 1 and 2 series by the controlled hydrogenation of the C-5–C-6 unsaturated bonds and α-selective (100%) reduction of the C-9 keto function, if necessary. Lithium aluminum hydride reagents modified by (*R*)- and (*S*)-2,2′-dihydroxy-1,1′-binaphthyl exhibit a unique kinetic discrimination in reduction of PGE type compounds. A protected 5,6-didehydro-PGF$_{2\alpha}$ has been transformed stereoselectively to PGI$_2$ by using intramolecular alkoxypalladation/depalladation as the key step.

Prostaglandins (PGs) are now recognized as significant local hormones controlling a multitude of significant physiological processes.[2] Development of the efficient chemical synthesis has been strongly required, because organic synthesis is the only means to supply sufficient quantities of these important but naturally scarcely occurring substances[2d] and to create the medicinally more cultivated artificial compounds.[2d] Although the methods developed by Corey[3] and the Upjohn Co.[2d,4] among others[5] have already been commercialized, elaboration of the shorter, efficient entries to natural PGs and the analogues is still desirable.[2d] We have pursued the realization of the convergent three-component coupling process, viz. the simultaneous assembly of the five-membered cyclic ketone unit and two side chains, in view of the directness and flexibility.[6]

Obviously, the ultimate goal along this line is, as illustrated by eq 1 (M = metal, X = halogen), the one-pot construction of

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[†] Dedicated to Professor E. J. Corey on the occasion of his 60th birthday.

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