was rapidly removed by rotary evaporator from a solution of about 1 mg of **33** in ether, and the appropriate solvent was immediately added. The solution was then placed in an NMR tube and sealed. The NMR tube was placed in a constant temperature bath at 25.0 °C. At periodic time intervals, the tube was analyzed by ^{19}F NMR (probe maintained at 25 °C). Depending on the solvent, the signal due to the CF_3CO_2H product appears 1.0–1.5 ppm upfield from that of the covalent trifluoroacetate.

Rates of solvolyses of trifluoroacetate **43** in HOAc and $(CF_3)_2CHOH$ were determined by UV spectroscopy at 290 nm.

Acknowledgment is made to the National Science Foundation for support of this research.

Supplementary Material Available: ^1H and ^{13}C NMR spectra for compounds **8** (R = 3,5-bis-CF_3), $CH_3CH(OH)CSNMe_2$, $(CH_3)_2C(OH)CSNMe_2$, **9** (Ar = Ph), **10**, **11**, **25**, **26**, **31**, and **42** (20 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

The Strain Energy of Cyclotetradecane Is Small

James S. Chickos,[†] Donald G. Hesse,[†] Sandra Y. Panshin,[‡,§] Donald W. Rogers,[⊥]
Martin Saunders,[‖] Philip M. Uffer,[‡] and Joel F. Liebman*[,‡]

Department of Chemistry, University of Missouri—St. Louis, St. Louis, Missouri 63121, Department of Chemistry and Biochemistry, University of Maryland, Baltimore County Campus, Baltimore, Maryland 21228-5398, Department of Chemistry, Long Island University, Brooklyn, New York 11201, and Department of Chemistry, Yale University, New Haven, Connecticut 06500

Received September 19, 1991

Contrary to earlier reports, we show the strain energy of cyclotetradecane is both small and similar to that of other moderately sized cycloalkanes. Our finding is derived by use of semiempirical rules, MM3 molecular mechanical calculations, chemical intuition, and new measurements of heats of sublimation (mean temperature = 39 °C, 23.4 kcal mol^{-1}; corrected to STP, 23.5 kcal mol^{-1}) and vaporization (mean temperature = 70 °C, 14.9; corrected to STP, 15.6 kcal mol^{-1}).

We wish to report that, contrary to results from earlier studies,[1,2] cyclotetradecane is nearly strainless. Cycloalkanes are conceptually among the simplest classes of organic compounds because they are composed of only carbon and hydrogen and of only one type of structural component. As such, they are important archetypes for our understanding of the interrelations of structure and energy for heterocyclic, substituted, and polycyclic systems. The results are applicable to crown ethers, cryptands, carcerands, and even more elegant complexing species,[3] as well as to highly functionalized derivatives such as the calicheamycins and esperamycins, and the other new enediyne antitumor agents.[4]

Regardless of the precise definition of strain energy and choice of the input parameters,[5] the values for cycloalkanes are not a monotonic function of ring size. Table I gives the values of these strain energies using the assumption that cyclohexane is strainless.[6] We find 3- and 4-membered rings are highly, and nearly identically, strained; 5- and 7-straddle cyclohexane are only moderately strained; 8–11-membered rings are all rather strained; and 12-membered and beyond generally have little strain.

Table I. Strain Energies (in kcal mol^{-1}) of the Cycloalkanes as a Function of Ring Size n and the Following Definition of Strain Energy

$$SE(g, (CH_2)_n) \equiv \Delta H_f[g, (CH_2)_n] - \tfrac{n}{6}\Delta H_f(g, (CH_2)_6)$$

n	SE	n	SE	n	SE
3	27.5	8	9.6	13	5.0
4	26.4	9	12.5	14	11.6
5	6.3	10	12.3	15	1.7
6	0	11	11.2	16	1.9
7	6.2	12	4.0	17	−3.5

Despite the diverse intricacies influencing the values for moderately sized rings, the value of the $n = 14$ species still seems badly out of line. We questioned whether the cyclotetradecane value is correct. One reason for our skepticism is that strain energy refers to gas-phase species at 25 °C and 1 atm, while most experimental measurements of heat of combustion (and thus the derived heat of formation) refer to condensed phases. About a decade ago, an empirical relation for predicting heats of vaporization

---

[†] University of Missouri—St. Louis.

[‡] University of Maryland Baltimore County.

[§] Present address: Department of Chemistry, Indiana University.

[⊥] Long Island University.

[‖] Yale University.

(1) The original thermochemical data on cyclotetradecane is found in: Frisch, M. A.; Bautista, R. G.; Margrave, J. L.; Parsons, C. G.; Wotiz, J. H. *J. Am. Chem. Soc.* **1964**, *86*, 335. For completeness, we note an earlier study that results in a heat of formation of solid cyclotetradecane of −89.5 ± 0.3 kcal mol^{-1} (Coops, J.; Van Kamp, H.; Lambregts, W. A.; Visser, B. J.; Dekker, H. *Rec. Trav. Chim.* **1960**, *79*, 1226).

(2) For a review of the strain energy of cycloalkanes and of other building blocks of strained molecules, see: Greenberg, A.; Liebman, J. F. *Strained Organic Molecules*; Academic Press: New York, 1978; Chapter 3 and numerous references cited therein. For a review of the thermodynamic properties of hydrocarbons, see: Domalski, E. S.; Hearing, E. D. *J. Phys. Chem. Ref. Data* **1988**, *17*, 1637.

(3) See, for example, the Nobel Prize lectures of: Cram, D. J.; Lehn, J. M.; Pedersen, C. J. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 1009, 90, and 1021, respectively.

(4) Lee, M. D.; Ellestad, G. A.; Borders, D. R. *Acc. Chem. Res.* **1991**, *24*, 235.

(5) Van Vechten, D.; Liebman, J. F. *Isr. J. Chem.* **1981**, *21*, 105.

(6) Since the standard heat of formation of gaseous cyclohexane is −29.5 (±0.2) kcal mol^{-1}, the heat of formation of the strainless CH_2 increment is taken to be −4.92 kcal mol^{-1}. (All otherwise unreferenced thermochemical information in this paper is taken from the archival and often "averaged" source: Pedley, J. B.; Naylor, R. D.; Kirby, S. P. *Thermochemical Data of Organic Compounds*, 2nd ed.; Chapman & Hall: London, 1986. Had we used the results of Frisch et al., op. cit. for the heat of formation of solid cyclotetradecane instead, we would have concluded that this species was strained by 12.1 kcal mol^{-1}.)

0022-3263/92/1957-1897$03.00/0

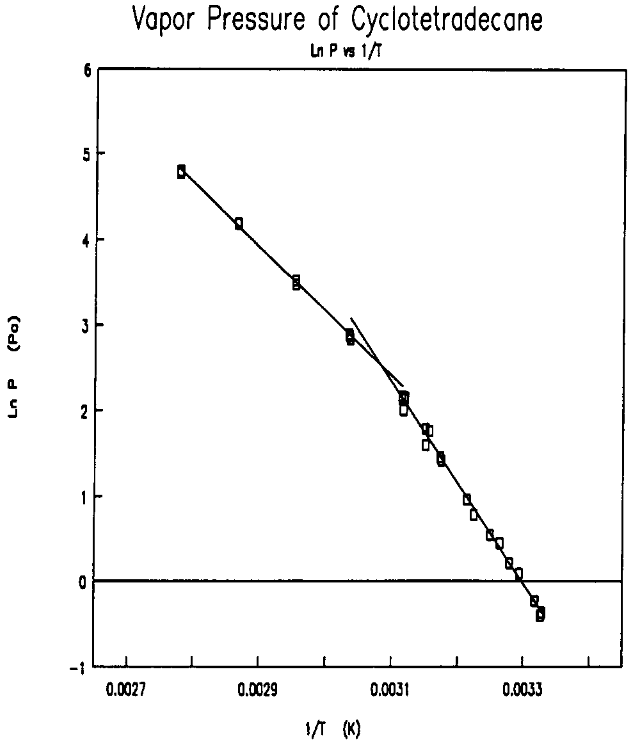

Figure 1. Plotted data for the heats of sublimation and vaporization of cyclotetradecane where we, respectively, find: $\ln P = (-11776 \pm 190)/T + (27.30 \pm 0.06)$; $r = 0.9978$ $\ln P = (-7508.8 \pm 91.4)/T + (14.14 \pm 0.03)$; $r = 0.9993$. The raw data is given in the supplementary material.

of arbitrary hydrocarbons under standard conditions, eq 1, was first presented[7]

$$\Delta H_v = 1.12\tilde{n}_c + 0.31n_Q + 0.71 \qquad (1)$$

Here, n_Q is the number of quaternary carbons, $\tilde{n}_c$ is the number of nonquaternary carbons, and 1.12, 0.31, and 0.71 are statistically derived parameters. This equation is typically accurate[7] to within ±1 kcal mol^{-1}.

The value predicted by eq 1 for the heat of vaporization of cyclotetradecane is 16.4 kcal mol^{-1}. Recall the identity expressed in eq 2:

$$\Delta H_{sub} \equiv \Delta H_{fus} + \Delta H_v \qquad (2)$$

Using the archival heat of sublimation of cyclotetradecane, 32.3 kcal mol^{-1}, we thus derive a heat of fusion of 15.9 kcal mol^{-1}. That the heat of fusion should nearly equal the heat of vaporization seems unlikely. Liquids and solids are generally more similar to each other than are liquids and gases. Using the recently reported heat of fusion for cyclotetradecane[8] of 6.9 kcal mol^{-1} at the melting point (T_M = 55 °C) and the plausible SEALE relation[9] for estimating heats of sublimation, eq 3, we derive a new heat of sublimation of 23.3 ± 1 kcal mol^{-1}. If this new value is correct, and we accept the literature value[2a] for the heat of formation of solid cyclotetradecane (−88.9 ± 0.3 kcal mol^{-1}), and then the heat of formation of the gaseous species is −65.6 kcal mol^{-1}. The old strain energy of cyclotetradecane is thus too high by 9 kcal mol^{-1}. The new value of the strain energy is 3.2 ± 1 kcal mol^{-1}, much more in line with our expectations.

$$\Delta H_{sub}(25\ °C) \approx \Delta H_{fus}(T_M) + \Delta H_v^{calc} \qquad (3)$$

Table II. Values for the Heats of Formation (in kcal mol^{-1}) of Gaseous Cyclotetradecane and Derived Strain Energies Relative to Cyclohexane

method for ΔH_f (g)	ΔH_f(g)	derived SE
Archival choice	−57.2	11.6
SEALE:[9] $\Delta H_f(s)^6 + \Delta H_{fus}{}^8$ + estimated $\Delta H_v{}^7$	−65.6	3.2
$\Delta H_f(s)^6$ + direct ΔH_s	−66.0	2.8
$\Delta H_f(s)^6$ + direct $\Delta H_s + 2R\Delta T$	−65.9	2.9
$\Delta H_f(s)^6 + \Delta H_{fus}{}^8$ + direct ΔH_v	−67.6	1.2
$\Delta H_f(s)^6 + \Delta H_{fus}{}^8$ + direct ΔH_v + "Sidgwick"	−66.9	1.9
mol mechanics (MM3[12] + stochastic optim[13])	−68.8	1.1[a]
Boltzmann weighting (MM3[12] + stochastic optim[13])	−68.5	1.4[a]

[a] Used MM3 calculated heat of formation of cyclohexane.

We did not rely solely on the above semiempirical relations. Rather, we directly measured the heat of sublimation and of vaporization of cyclotetradecane and plotted the results in Figure 1. Following techniques and corrections described elsewhere,[10] the former heat was found to be 23.4 kcal mol^{-1} when measured at a mean temperature of 39 °C and then corrected to standard conditions by but +0.1 kcal mol^{-1}, the recommended $2R\Delta T$. In this case, theory and experiment are in excellent agreement here. Relatedly, the heat of vaporization was measured at a mean temperature of 70 °C and found to be 14.9 kcal mol^{-1}. Using a revived and revised Sidgwick's correction,[11] eq 4, the standard heat of vaporization is found to be 15.6 kcal mol^{-1}. This standard value of ΔH_v is in satisfactory agreement with that predicted by eqs 1–3 upon assignment of plausible and typical error bars[7,9] of ca. 1 kcal mol^{-1}.

$$[\Delta H_v(T) - \Delta H_v(25\ °C)]/(T - 25) = -0.014 \qquad (4)$$

Finally, we have employed molecular mechanics, using the MM3 force field[12] and the stochastic method[13] of optimizing molecular geometries, to predict a heat of formation of −68.8 kcal mol^{-1} for the lowest energy conformer of cyclotetradecane. The plethora of almost as low energy conformers[14] forces us to derive a heat of formation of the equilibrium mixture. Boltzmann weighting the four lowest energy conformers, we derive a heat of formation of gaseous cyclotetradecane of −68.5 kcal mol^{-1}, a value almost within the experimental error bars. Combined with the MM3 calculated heat of formation of cyclohexane[12a] (off by 0.46 kcal mol^{-1} from experiment), we deduce that the

---

(7) Chickos, J. S.; Hyman, A. S.; Ladon, L. H.; Liebman, J. F. *J. Org. Chem.* **1981**, *46*, 4294.

(8) Chickos, J. S.; Braton, C. M.; Hesse, D. G.; Liebman, J. F. *J. Org. Chem.* **1991**, *56*, 927.

(9) Chickos, J. S.; Annunziata, R.; Ladon, L. H.; Hyman, A. S.; Liebman, J. F. *J. Org. Chem.* **1986**, *51*, 4311.

(10) Chickos, J. S. In *Molecular Structure and Energetics: Physical Measurements*; Liebman, J. F., Greenberg, A., Eds.; VCH: New York, 1987; Vol. 2, Chapter 3.

(11) The earliest citation we know of for this relation is: Sidgwick, N. V. *The Covalent Link in Chemistry*; Cornell University Press: Ithaca, 1933; p 104, where it was "derived" from latent heat data on a "melange" of 13 (both organic and inorganic, associated and not) species and the derived constant equaled −0.013. We opted to choose the temperature *T* to be the boiling point with the "most reliable" hydrocarbon data (31 species) in: Majer, V.; Svoboda, V. *Enthalpies of Vaporization of Organic Compounds A Critical Review and Data Compilation*; Blackwell Scientific Publications: Oxford, 1985. For each species, we considered their recommended heat of vaporization and standard heat of vaporization. Since these two quantities were the same to better than 3%, we used their average resulting in our presented average "Sidgwick's constant" of −0.014 kcal (mol-K)$^{-1}$.

(12) (a) Allinger, N. L.; Yuh, Y. H.; Lii, J.-H. *J. Am. Chem. Soc.* **1989**, *111*, 8551. (b) Lii, J.-H.; Allinger, N. L. *Ibid.* **1989**, *111*, 8566, 8576.

(13) (a) Saunders, M. *J. Am. Chem. Soc.* **1987**, *109*, 3150; *J. Comput. Chem.* **1989**, *10*, 203. (b) Saunders, M.; Houk, K. N.; Wu, Y.-D.; Still, W. C.; Lipton, M.; Chang, G.; Guida, W. C. *J. Am. Chem. Soc.* **1990**, *112*, 1419. (c) Saunders, M.; Krause, N. *Ibid.* **1990**, *112*, 1791.

(14) Both the liquid and the "high temperature" solid form of cyclotetradecane have been shown by high-resolution IR spectroscopy to be composed of multiple conformers as well: Shannon, V. L.; Strauss, H. L.; Snyder, R. G.; Elliger, C. A.; Mattice, W. L. *J. Am. Chem. Soc.* **1989**, *111*, 1949.

strain energy of cyclotetradecane is but 1.4 kcal mol^{-1}.

In summary, we have examined cyclotetradecane using an approach that combines intuition about ring-size effects, estimates and measurement of heats of phase changes, and molecular mechanical calculations. Table II summarizes all of the individual results, where all unreferenced quantities are from the current study. We conclude that the strain energy of cyclotetradecane is in line with comparably sized cycloalkanes.

Acknowledgment. Acknowledgment is made (D.W.R.) to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research and to LIU for a grant of released time. Likewise, J.S.C. thanks the IRQ fund, administed by the University of Missouri—St. Louis, and J.F.L. likewise thanks the Laboratory of Chemical Science and Technology, National Institute of Standards and Technology, for partial support of this research. The authors would also like to thank Norman L. Allinger, Arthur Greenberg, Robert G. Snyder, and Herbert L. Strauss for discussions on the energetics and conformations of alicyclic species.

Supplementary Material Available: The salient MM3 output for the lowest four conformers of cyclotetradecane and both the raw and plotted heat of vaporization and sublimation data (23 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

Dication Formation by Oxidation of Hydrocarbons with SbF_5. Correlation between Ionization Potential, Heat of Formation, and Dication Formation

Nancy S. Mills

Department of Chemistry, Trinity University, San Antonio, Texas 78212-7200

Received September 19, 1991

The ability of unsaturated hydrocarbons to be oxidized to dications by SbF_5 was examined through AM1, MNDO, and MINDO/3 calculations on 53 compounds whose reactions under these conditions were reported in the literature. A positive correlation existed for first ionization potentials calculated by AM1 for substituted and unsubstituted polycyclic aromatic hydrocarbons, with oxidation to dications occurring when the ionization potential was $\leq$8.3 eV. The correlation was poor for nonbenzenoid precursors. A much better correlation for all hydrocarbon precursors was with the difference between the heats of formation of the dication and its neutral precursor ($\Delta\Delta H_f$). Both AM1 and MINDO/3 were equally satisfactory in their correlation with $\Delta\Delta H_f$ ceilings of 463 ± 4 kcal/mol (AM1) and 430 ± 4 kcal/mol (MINDO/3) for dication formation.

We are interested in preparing novel hydrocarbon dications from unsaturated precursors by oxidation with SbF_5 in SO_2ClF, particularly those which might possess nonclassical structures like the pyramidal $C_6(CH_3)_6$ dication.[1] Because the synthesis of the unsaturated precursor can involve a major committment of time and effort, it was important to us to be able to easily identify those unsaturated precursors which are most likely to form dications under our conditions. We report here data from AM1, MNDO, and MINDO/3 calculations on 53 compounds whose attempted oxidation by SbF_5 in SO_2ClF was reported in the literature.

There are two types of data from molecular orbital calculations which could be used with experimental data to predict the likelihood of dication formation. Since the formation of dications from unsaturated precursors involves the loss of electrons, the magnitude of the ionization potential(s) might allow precursors to be grouped according to whether they could or could not form dications. Similarly, a comparison of the energy of the dication ($\Delta H_{\text{formn dication}}$) with the energy of the neutral species ($\Delta H_{\text{formn neutral hydrocarbon}}$) or $\Delta\Delta H_f$ might allow a similar grouping of precursors.

Results

Calculation of Ionization Potentials. We chose to calculate first and second ionization potentials using the AM1[2] method because it reliably reproduces higher ionization energies, as does the MNDO[3] method, and because we intended ultimately to examine molecules with moderate to severe steric congestion and the AM1 method is superior to MNDO in dealing with sterically congested molecules.[4] We chose not to use the PM3 method[5] because it has not yet received the verification in the literature to date of AM1. We chose to calculate both first and second ionization potentials for a subset of the precursors to be considered because it was not obvious that the same trends would appear in the formation of cation radicals and in the formation of dications. Because the calculation of the first ionization potential is based on Koopman's theorem, in which all orbitals are unchanged upon going from the molecule to the cation radical, we performed a closed-shell calculation of the second ionization potential using the geometry calculated for the neutral molecule which was assigned a charge of 1 in the calculation. That is, the cation radical was assumed to have the geometry of the neutral molecule for the purpose of calculating its ionization potential, or the energy required to make the dication.

Previous work with a variety of benzenoid aromatic hydrocarbons[6] found that their ability to form dications, as opposed to cation radicals, could be rationalized by a

---

(1) Hogeveen, H.; Kwant, P. W. *J. Am. Chem. Soc.* **1974**, *96*, 2208–2214.

(2) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902–3909.

(3) Dewar, M. J. S.; Thiel, W. *J. Am. Chem. Soc.* **1977**, *99*, 4899–4907.

(4) Müller, M.; Hohlneicher, G. *J. Am. Chem. Soc.* **1990**, *112*, 1273–1274.

(5) Stewart, J. J. P. *J. Comput. Chem.* **1989**, *10*, 221–264.

(6) Forsyth, D. A.; Olah, G. A. *J. Am. Chem. Soc.* **1976**, *98*, 4086–4090.

0022-3263/92/1957-1899$03.00/0 © 1992 American Chemical Society