ferences in the efficiency of internal conversion to this excited state. The maximum in the quantum yield observed at 350 nm implies that either a more efficient internal conversion occurs at this wavelength or that the reactive state lies at this energy. The latter possibility is discounted, since an efficient formation of chloramine is also observed at 400 nm. Thermal population of the 350 nm level following excitation at 400 nm seems unlikely, since the quantum yields at these wavelengths were found to be independent of temperature. It is possible that excitation at 350 nm results in an appreciable direct population of an azide excited state, since Gray, *et al.*, have observed a weak absorption ($\epsilon < 20$ M^{-1} cm^{-1}) at approximately 300 nm in alkylazides.[28]

Although the sensitization experiments were undertaken to determine the energy and multiplicity of the reactive level, failure to sensitize the photochemical reaction does not allow conclusions to be drawn regarding the spin or energy of the reactive level.

Conclusion

Unlike the photochemical reactions of first-row transition metal–azidopentaammine complexes, photolysis of azidopentaammineiridium(III) leads exclusively to the formation of the coordinated nitrene intermediate.

This difference in photochemical behavior is attributed to an increased stability of the iridium(III) nitrene intermediate. The size of the outer d orbitals of iridium are larger than for first-row transition metals, permitting greater dπ–pπ interaction which results in a more stable coordinated nitrene. Furthermore a redox mode of reaction is unfavorable, since the plus two oxidation state of iridium is not stable in its pentaammine complex.

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Critical Evaluation of Molecular Mechanics

Edward M. Engler, Joseph D. Andose, and Paul von R. Schleyer*

Contribution from the Department of Chemistry, Princeton University,
Princeton, New Jersey 08540. *Received May 17, 1973*

Abstract: The ability of molecular mechanics (empirical force field calculations) to estimate structures and enthalpies of large organic molecules reliably is probed through extensive calculations on alkanes using two significantly different force field models, Allinger's and one described in the present work. Most of the available data are reproduced with an accuracy rivaling that achieved by the experimental methods. Bond lengths are generally calculated within 0.01 Å of the experimental values, except for four-membered rings and small polycyclic systems where 1,3-nonbonded interactions, neglected in our treatment, become important. Bond angles are reproduced with an accuracy of 1–2°; somewhat larger errors (3–5°) are noted for the bridgehead angles at the junction of two four-membered rings. The standard deviation between calculated and experimental heats of formation for a balanced set of acyclic, cyclic, and polycyclic alkanes used in the parameterization of the force field (39 compounds) is 0.83 kcal/mol (present work) and 1.03 kcal/mol (Allinger's force field). Both force fields are applied to the prediction of the heats of formation of 84 alkanes of diverse structural type. While agreement between the two force field calculations is within 2.0 kcal/mol for 55 of the compounds, some large discrepancies are found for molecules composed mainly of CH groups. The largest disagreement is 45.5 kcal/mol calculated for dodecahedrane (20 CH units). The lack of sufficient, reliable experimental data prevents accurate parameterization of the force field for molecules of this type. Calculations on medium-ring cycloalkanes indicate that these systems are more flexible than previously suggested by molecular mechanics. Earlier studies which imposed artificial symmetry constraints during minimization lead to higher energies. Relative energies are determined more reliably than absolute enthalpy calculations since defects in the method tend to cancel. We now support Allinger's conclusion that the molecular mechanics method, in principle, must be considered to be competitive with experimental determination of the structures and enthalpies of molecules.

Quantitative interpretation of organic chemical phenomena requires the availability of accurate thermochemical information. Experimental data are sparse[1] and are not being gathered at a rapid rate. A method is needed whereby such energies can be estimated inexpensively, easily, and with high expectation of accuracy, even when the molecules of interest have not as yet been prepared. At the present time, *molecular mechanics* calculations[2] represent the best approach to a solution of this problem.[3]

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(1) (a) J. D. Cox and G. Pilcher, "Thermochemistry of Organic and Organometallic Compounds," Academic Press, New York, N. Y., 1970; (b) D. R. Stull, E. F. Westrum, Jr., and G. C. Sinke, "The Chemical Thermodynamics of Organic Compounds," Wiley, New York, N. Y., 1969; (c) "Bulletin of Thermodynamics and Thermochemistry," E. F. Westrum, Jr., Ed., University of Michigan, issued yearly; (d) S. W. Benson, F. R. Cruickshank, D. M. Golden, G. R. Haugen, H. E. O'Neal, A. S. Rodgers, R. Shaw, and R. Walsh, *Chem. Rev.*, **69**, 279 (1969); (e) M. Kh. Karpet'yants and M. K. Karpet'yants, "Handbook of Thermodynamic Constants of Inorganic and Organic Compounds," Ann Arbor-Humphrey Science Publishers, Ann Arbor, Mich., 1970.

(2) For a review of this computational approach see J. D. Williams, P. J. Stang, and P. v. R. Schleyer, *Annu. Rev. Phys. Chem.*, **19**, 531 (1968); Professor S. Lifson (private communication) prefers *Empirical force field calculations* as a descriptive term.

(3) While important progress has been realized in this area using quantum mechanical procedures, difficulties persist in the achievement of the desired degree of accuracy for large organic molecules. For recent reviews, see G. Klopman and B. O'Leary, *Fortsch. Chem. Forsch.*,

In the molecular mechanics approach outlined by Westheimer,[4] a molecule is viewed as a collection of particles held together by simple harmonic or elastic forces. Such forces are defined in terms of potential energy functions of the internal coordinates of the molecule and make up what is termed the molecular force field. Early calculations in this area by Westheimer on the rates of racemization of substituted biphenyls[4] and later by Hendrickson on the preferred conformations of medium-ring cycloalkanes[5a] were performed on fixed geometric conformations. The procedure was later refined by Wiberg[6] with the introduction of an energy minimization scheme whereby the energy minimum with respect to all the internal coordinates is sought. Since then, the number of papers dealing with molecular mechanics have grown dramatically. Table I summarizes some of the many areas in which this method has found application. Much of the literature, however, focuses on the calculation of structures rather than energies, or on applications directed toward a specific problem or class of molecules. The result of such limited applications is the propagation of many different force fields, each applicable only to the specific area or problem for which it was parameterized. For example, while a number of force fields have been developed to treat simple acyclic and cyclic alkanes,[5-9] they are not in general applicable to sterically congested or polycyclic systems without reparameterization. Furthermore, since molecular mechanics force fields involve a fairly large number of adjustable parameters which have been fitted in most instances to a relatively small body of experimental data, the method cannot be made entirely free of the problem of overparameterization. Thus, good agreement of calculated results within a limited set of experimental data does not necessarily establish the reliability of the force field model. Entirely erroneous results might be obtained when the calculations are extended to a larger number of molecules. Another problem with many of the force fields is that they are restricted to the calculations of minimum energy conformations of single molecules and have not been extended to comparisons of energies for molecules which differ in substitution type, *e.g.*, differences in number of quaternary, tertiary, secondary, and primary units. Such a comparison requires the evaluation of heats of formation (see discussion below). If molecular mechanics is to have any credibility as a calculation method, force field models must be developed which are applicable to a wide variety of structural types, *e.g.*,

Table I. Applications of Molecular Mechanics

Areas of application[a]	Ref
Simple acyclic and cyclic alkanes	*b, c, d, e, f, g, h, i*
Polycycloalkanes	*h, i, j, k, l*
Torsional barriers in substituted ethanes	*m, n, o*
Functional groups (olefins, carbonyls, halogens, oxygen, and nitrogen containing compounds)	*p, q, r, s, t, u, v, w, x, y, z, aa, ww*
Aromatics	*x, bb, cc, dd, ee*
Silanes, group IV organometallics, transition metal complexes	*ff, gg, hh, ii, jj*
Polymer and polypeptide conformations	*kk, ll, mm, xx*
Radical and carbonium ion reactivities (solvolytic reactivity)	*nn, oo*
Reactivity calculations, transition-state evaluations	*pp, qq, rr*
Conformational interconversions, potential energy surfaces	*b, c, f, h, k, ss, tt, uu, vv*

[a] These areas are rather loosely defined and not necessarily independent of each other. [b] Reference 5. [c] Reference 6. [d] Reference 7. [e] Reference 8. [f] Reference 9. [g] Reference 10b. [h] Reference 10a. [i] Reference 20. [j] Reference 18. [k] Reference 23. [l] N. M. Zarinov, V. G. Dashevskii, and V. A. Naumov, *Bull. Acad. Sci., USSR, Div. Chem. Sci.*, **20**, 1542 (1971); N. M. Zarinov, V. G. Dashevskii, and V. A. Naumov, *ibid.*, 1848 (1970). [m] H. Heublen, R. Kühmstedt, P. Kadura, and H. Dawczynski, *Tetrahedron*, **26**, 81 (1970); H. Heublen, R. Kühmstedt, H. Dawczynski, and P. Kadura, *ibid.*, **26**, 91 (1970). [n] A. Goursot-Leray, H. Bodot, *ibid.*, **27**, 2133 (1971). [o] R. J. Abraham and K. Parry, *J. Chem. Soc. B*, 539 (1970). [p] Reference 11. [q] Reference 12. [r] Reference 17. [s] Reference 19. [t] F. Zuccarello, G. Buemi, and G. Favini, *J. Mol. Struct.*, **8**, 459 (1971), and earlier work. [u] N. C. Cohen, *Tetrahedron*, **27**, 789 (1971). [v] J. Fournier and B. Waegell, *ibid.*, **26**, 3195 (1970); J. Fournier and B. Waegell, *ibid.*, **28**, 3407 (1972). [w] A. Warshel, M. Levitt, and S. Lifson, *J. Mol. Spectrosc.*, **33**, 84 (1970). [x] T. Beringhelli, A. Gavezzotti, and M. Simonetta, *J. Mol. Struct.*, **12**, 333 (1972); G. Casalone and M. Simonetta, *J. Chem. Soc. B*, 1180 (1971); G. Casalone, C. Mariani, A. Mugnoli, and M. Simonetta, *Mol. Phys.*, **15**, 339 (1968). [y] I. D. Blackburne, R. P. Duke, R. A. Y. Jones, A. R. Katritzky, and K. A. F. Record, *J. Chem. Soc., Perkin Trans. 2*, 332 (1973). [z] A. A. Lugovskoi and V. G. Dashevskii, *J. Struct. Chem. (USSR)*, **13**, 105, 112 (1972). [aa] V. G. Dashevskii, V. A. Naumov, and N. M. Zaripov, *ibid.*, **11**, 687 (1970). [bb] A. Warshel and M. Karplus, *J. Amer. Chem. Soc.*, **94**, 5612 (1972). [cc] V. G. Dashevskii and A. I. Kitaigorodskii, *Theor. Exp. Chem. (USSR)*, **3**, 18, 22 (1967); V. G. Dashevskii, *J. Struct. Chem. (USSR)*, **6**, 850 (1965); A. I. Kitaigorodskii and V. G. Dashevskii, *Tetrahedron*, **24**, 5917 (1968). [dd] Reference 21. [ee] Reference 14. [ff] Reference 13. [gg] R. J. Ouellette, *J. Amer. Chem. Soc.*, **94**, 7674 (1972). [hh] R. J. Ouellette, D. Baron, J. Stolfo, A. Rosenblum, and P. Weber, *Tetrahedron*, **28**, 2163 (1972). [ii] M. Dwyer and G. H. Searle, *J. Chem. Soc., Chem. Commun.*, 726 (1972). [jj] M. R. Snow, *J. Amer. Chem. Soc.*, **92**, 3610 (1970); D. A. Buckingham, I. E. Maxwell, A. M. Sargeson, and M. R. Snow, *ibid.*, **92**, 3617 (1970). [kk] P. J. Flory, J. E. Mark, and A. Abe, *ibid.*, **88**, 639 (1966); A. Abe, R. L. Jernigan, and P. J. Flory, *ibid.*, **88**, 631 (1966). [ll] H. A. Scheraga, *Advan. Phys. Org. Chem.*, **6**, 103 (1968); H. A. Scheraga, *Chem. Rev.*, **71**, 195 (1971). [mm] J. L. DeCoen, *J. Mol. Biol.*, **49**, 405 (1970). [nn] Reference 22. [oo] V. R. Koch and G. J. Gleicher, *J. Amer. Chem. Soc.*, **93**, 1657 (1971). [pp] E. W. Garbisch, Jr., *ibid.*, **87**, 505 (1965); E. W. Garbisch, Jr., S. M. Schildcrout, D. B. Patterson, and C. M. Sprecher, *ibid.*, **87**, 2932 (1965). [qq] M. Simonetta, G. Favini, C. Mariani, and P. Gramaccioni, *ibid.*, **90**, 1280 (1968). [rr] V. G. Dashevskii and A. A. Lugovskoi, *J. Mol. Struct.*, **12**, 39 (1972). [ss] J. R. Pedersen, *Acta Chem. Scand.*, **26**, 3181 (1972). [tt] K. B. Wiberg and R. H. Boyd, *J. Amer. Chem. Soc.*, **94**, 8426 (1972). [uu] G. Montaudo, P. Finocchiaro, and S. Caccamese, *J. Org. Chem.*, **38**, 170 (1973). [vv] H. G. Schmid, A. Jaeschke, H. Friebolin, S. Kabuss, and R. Mecke, *Org. Magn. Resonance*, **1**, 163 (1969). [ww] Reference 9g. [xx] M. Levitt and S. Lifson, *J. Mol. Biol.*, **46**, 269 (1969).

15, 445 (1970). J. A. Pople and D. L. Beveridge, "Approximate Molecular Orbital Theory," McGraw-Hill, New York, N. Y., 1970. MINDO/2 is the most extensively tested semiempirical method; see M. J. S. Dewar and E. Haselbach, *J. Amer. Chem. Soc.*, **92**, 590 (1970).

(4) F. H. Westheimer in "Steric Effects in Organic Chemistry," M. S. Newman, Ed., Wiley, New York, N. Y., 1956, Chapter 12; *cf.* F. H. Westheimer and J. E. Mayer, *J. Chem. Phys.*, **14**, 733 (1946); F. H. Westheimer, *ibid.*, **15**, 252 (1947).

(5) (a) J. B. Hendrickson, *J. Amer. Chem. Soc.*, **83**, 4537 (1961); **84**, 3355 (1962); **86**, 4854 (1964); (b) J. B. Hendrickson, *ibid.*, **89**, 7036, 7043, 7047 (1967).

(6) K. B. Wiberg, *ibid.*, **87**, 1070 (1965).

(7) R. G. Snyder and J. H. Schachtschneider, *Spectrochim. Acta*, **21**, 169 (1965).

(8) E. J. Jacob, H. B. Thompson, and L. S. Bartell, *J. Chem. Phys.*, **47**, 3736 (1967).

(9) (a) S. Lifson and A. Warshel, *ibid.*, **49**, 5116 (1968); (b) M. Bixon and S. Lifson, *Tetrahedron*, **23**, 769 (1967); (c) M. Bixon, H. Dekker, J. D. Dunitz, H. Eser, S. Lifson, C. Mosselman, J. Sicher, and M. Svoboda, *Chem. Commun.*, 360 (1967); (d) J. D. Dunitz, H. Eser, M. Bixon, and S. Lifson, *Helv. Chim. Acta*, **50**, 1572 (1967); (e) A. Warshel and S. Lifson, *Chem. Phys. Lett.*, **4**, 225 (1969); (f) A. Warshel and S. Lifson, *J. Chem. Phys.*, **53**, 582 (1970); (g) O. Ermer and S. Lifson, *J. Amer. Chem. Soc.*, **95**, 4121 (1973).

acyclic, cyclic, and polycyclic structures, and which have been parameterized against a large body of experimental data. Recently, two force field models have appeared which have attempted to incorporate these features.

Allinger and coworkers in a series of papers have successively improved their calculations for treating alkanes[10] and have extended them to olefins,[11] ketones,[12] silanes,[13] and conjugated systems,[14] as well as applying them to the evaluation of a variety of problems in conformational analysis[15] and chemical equilibria.[16] An earlier paper[17] treated organic molecules containing nitrogen, oxygen, and halogen but has yet to be updated with the newest alkane force field.[10a] Also, several groups have reported calculations with modified versions of Allinger's force field.[18,19] Allinger's force field for alkanes is the most extensively tested model published to date. A wide variety of thermodynamic and structural data have been reproduced with an impressive degree of accuracy.

The other force field model is that of Boyd's group which has been parameterized on a smaller body of experimental data to treat acyclic, cyclic, and polycyclic alkanes,[20] as well as some aromatic systems.[21] The Boyd force field, in contrast to Allinger's, has been developed to evaluate not only thermodynamic and structural data but vibrational frequencies as well. Lifson and Warshel[9a] were the first to include the ability to calculate vibrational spectra into their force field model. Furthermore, parameters were optimized by least-squares fit. However, their method has only been applied to simple acyclic alkanes, cycloalkanes, and olefins.[9] Boyd's work considers a larger variety of structural types. In Boyd's force field, in order to achieve agreement with the experimental data in all three areas, high accuracy in any one area was sacrificed. While consideration of all pertinent experimental data is, in principle, the preferred approach to arrive at a reliable force field, the sparsity of vibrational data for polycyclic alkanes jeopardizes the reliability of such calculations. In order to obtain all this information from the calculations to a useful degree of accuracy, additional interaction potentials and other refinements seem to be required.[7,9] In the absence of additional experimental vibrational data, it is difficult to justify the addition of more parameters. As with any empirical method, the results can be expected to be no better than the data from which they were derived. Thus, in spite of all that has been published to date, Allinger's force field model represents the only one directed toward the calculation of heats of formation and geometries of a structurally diverse class of molecules, which achieves a reasonable degree of agreement with most of the available experimental data.

At Princeton, we have been involved in the application of molecular mechanics to aid in the solution and evaluation of a wide variety of chemical problems in carbonium ion reactivity[22] and in conformational analysis.[23] Through successive stages of reparameterization and extension to an ever widening class of structurally diverse systems, a force field model has emerged, independently developed and significantly different from that derived by Allinger's group. Our aim has been essentially that of Allinger's: to obtain a *simple, generally applicable* force field model, extensively substantiated by experimental data, which will accurately calculate the heats of formation and structures of large organic molecules.

We propose a critical evaluation of the predictive abilities of the molecular mechanics method through comparison of results obtained by both Allinger's and our own force fields. Areas of agreement and disagreement should provide a truer gauge of the predictive ability and accuracy of such calculations; clues to possible improvements of the force field may also be provided. We restrict our calculations to saturated hydrocarbons not only because the majority of experimental thermodynamic data deals with such substances but also because they form the foundation upon which calculations on functionalized molecules must be based.

Force Field Description

In Westheimer's pioneering work on molecular mechanics,[4] the steric energy of a molecule was considered to arise from various strain-producing mechanisms defined in terms of potential energy functions of the structural parameters, *i.e.*, bond angles θ, torsional angles ϕ, bond lengths r, and nonbonded distances d (eq 1). Certain structural features are recognized as

$$E_{\text{steric}} = E(\theta) + E(r) + E(\phi) + E(d) \qquad (1)$$

"normal" or "strain-free" and deviations from these values lead to an increase in the strain energy.

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(10) (a) N. L. Allinger, M. T. Tribble, M. A. Miller, and D. W. Wertz, *J. Amer. Chem. Soc.*, **93**, 1637 (1971); (b) N. L. Allinger, J. A. Hirsch, M. A. Miller, I. J. Tyminski, and F. A. Van-Catledge, *ibid.*, **90**, 1199 (1968); N. L. Allinger, M. A. Miller, F. A. Van-Catledge, and J. A. Hirsch, *ibid.*, **89**, 4345 (1967).

(11) (a) N. L. Allinger and J. T. Sprague, *ibid.*, **94**, 5734 (1972); (b) N. L. Allinger, J. A. Hirsch, M. A. Miller, and I. J. Tyminski, *ibid.*, **90**, 5773 (1968).

(12) N. L. Allinger, M. T. Tribble, and M. A. Miller, *Tetrahedron*, 28, 1173 (1972).

(13) M. T. Tribble and N. L. Allinger, *ibid.*, **28**, 2147 (1972).

(14) N. L. Allinger and J. T. Sprague, *J. Amer. Chem. Soc.*, **95**, 3893 (1973).

(15) (a) N. L. Allinger and M. T. Tribble, *Tetrahedron Lett.*, 3259 (1971); (b) N. L. Allinger, M. T. Tribble, and J. T. Sprague, *J. Org. Chem.*, 37, 2423 (1972).

(16) (a) N. L. Allinger and M. T. Wuesthoff, *ibid.*, **36**, 2051 (1971); (b) N. L. Allinger and F. Wu, *Tetrahedron*, **27**, 5093 (1971); (c) N. L. Allinger and M. T. Tribble, *ibid.*, 28, 1191 (1972); (d) N. L. Allinger and J. H. Siefert, *J. Amer. Chem. Soc.*, **94**, 8082 (1972).

(17) N. L. Allinger, J. A. Hirsch, M. A. Miller, and I. J. Tyminski, *ibid.*, **91**, 337 (1969).

(18) R. J. Ouellette, J. D. Rawn, and D. Baron, Abstracts, 164th National Meeting of the American Chemical Society, New York, N. Y., April 27, 1972, ORGN 31.

(19) (a) C. Altona and M. Sundaralingam, *J. Amer. Chem. Soc.*, **92**, 1995 (1970); (b) C. Altona and M. Sundaralingam, *Tetrahedron*, **26**, 925 (1970); (c) C. Altona and H. Hirschmann, *ibid.*, **26**, 2173 (1970).

(20) (a) S. Chang, D. McNally, S. Shary-Tehrany, M. J. Hickey, and R. H. Boyd, *J. Amer. Chem. Soc.*, **92**, 3109 (1970); (b) R. H. Boyd, S. N. Sanwal, S. Shary-Tehrany, and D. McNally, *J. Phys. Chem.*, **75**, 1264 (1971).

(21) (a) R. H. Boyd, *J. Chem. Phys.*, **49**, 2574 (1968); (b) C. Shieh, D. McNally, and R. H. Boyd, *Tetrahedron*, **25**, 3653 (1969).

(22) (a) G. J. Gleicher and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **89**, 582 (1967); (b) P. v. R. Schleyer, P. R. Isele, and R. C. Bingham, *J. Org. Chem.*, **33**, 1239 (1968); (c) R. C. Bingham, W. F. Sliwinski, and P. v. R. Schleyer, *ibid.*, **92**, 3471 (1970); (d) R. C. Bingham and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **93**, 3189 (1971); (e) R. C. Bingham and P. v. R. Schleyer, *Tetrahedron Lett.*, 27 (1971); (f) A. Karim, M. A. McKervey, E. M. Engler, and P. v. R. Schleyer, *ibid.*, 3987 (1971); (g) J. L. Fry, E. M. Engler, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **94**, 4628 (1972).

(23) (a) E. M. Engler, L. Chang, and P. v. R. Schleyer, *Tetrahedron Lett.*, 2525 (1972); (b) T. M. Gorrie, E. M. Engler, R. C. Bingham, and P. v. R. Schleyer, *ibid.*, 3039 (1972); (c) E. M. Engler, K. R. Blanchard, and P. v. R. Schleyer, *J. Chem. Soc., Chem. Commun.*, 1210 (1972); (d) J. Slutsky, E. M. Engler, and P. v. R. Schleyer, *ibid.*, 685 (1973); (e) E. M. Enler, M. Farcasiu, A. Sevin, J. M. Conse and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **95**, 5769 (1973).

Table II. Experimental and Calculated Enthalpies and Strain Energies (kcal/mol)[a]

	$\Delta H_f°$ (gas, 25°)			Strain energy (gas, 25°)	
		Calcd		Calcd	
Hydrocarbon	Exptl	Present study[b]	Allinger[c]	Present study[b]	Allinger[c]
Ethane	−20.24	−20.59	−20.02	−0.49	−0.02
Propane	−24.83	−25.79	−25.27	−0.56	−0.11
n-Butane	−30.60[d]	−31.03	−29.90	−0.68	−0.48
n-Pentane	−35.56[d]	−36.32	−35.94	−0.83	−0.37
Isobutane	−32.41	−33.19	−32.21	−0.88	−0.10
2-Methylbutane	−36.94[d]	−37.32	−36.69	0.12	0.66
2-Methylpentane	−41.99[d]	−42.61	−42.12	−0.04	0.37
3-Methylpentane	−41.33[d]	−41.15	−41.13	1.42	1.36
2,3-Dimethylbutane	−42.88[d]	−42.57	−42.42	1.95	1.90
Neopentane	−40.14	−41.93	−41.02	−1.43	−0.80
2,2-Dimethylbutane	−44.48	−44.88	−44.60	0.74	0.81
3,3-Dimethylpentane	−48.08	−47.18	−47.55	3.58	3.05
2,2,3-Trimethylbutane	−48.87	−48.94	−49.10	3.77	3.26
2,2,3,3-Tetramethylbutane	−53.83	−53.19	−53.81	7.71	6.66
Cyclobutane	+6.78	+5.78	+5.52	26.30	26.28
Cyclopentane	−18.44	−18.37	−18.09	7.28	7.86
Cyclohexane	−29.50	−29.35	−29.93	1.43	1.21
Cycloheptane	−28.22	−28.26	−28.50	7.65	7.83
Cyclooctane	−29.73	−29.16	−29.26	11.88	12.26
Cyclononane	(−31.73)[e]	−30.70	−31.25	15.47	15.46
Cyclodecane	(−36.29)[e]	−34.93	−37.40	16.37	14.50
Cycloundecane	(−42.87)[e]	−41.11	−43.28	15.32	13.81
Cyclododecane	(−55.03)[e] (−50.50)[f]	−49.77	−52.46	11.79	9.82
Methylcyclopentane	−25.50	−26.20	−25.20	6.53	7.70
Methylcyclohexane	−36.98	−36.99	−37.06	0.87	1.03
1,1-Dimethylcyclohexane	−43.23	−43.50	−43.85	2.39	2.35
cis-1,2-Dimethylcyclohexane	−41.13	−41.55	−41.83	3.39	3.21
trans-1,2-Dimethylcyclohexane	−42.99	−43.20	−43.25	1.74	1.79
cis-Bicyclo[4.2.0]octane	−6.1[g]	−4.39	−3.47	30.71	31.98
cis-Bicyclo[3.3.0]octane	−22.3[g]	−22.61	−20.68	12.49	14.77
trans-Bicyclo[3.3.0]octane	−15.9[g]	−15.87	−15.49	19.23	19.96
cis-Bicyclo[4.3.0]nonane	−30.38	−30.37	−29.94	9.86	10.71
trans-Bicyclo[4.3.0]nonane	−31.42	−31.47	−31.11	8.76	9.54
cis-Bicyclo[4.4.0]decane	−40.43	−40.71	−41.20	4.65	4.63
trans-Bicyclo[4.4.0]decane	−43.52	−43.42	−43.78	1.94	2.05
Norbornane	−12.42[g]	−12.99	−13.48	16.98	16.78
1,4-Dimethylnorbornane	−30.63[h]	−32.12	−32.11	14.23	14.37
2,3-Dimethylnorbornane	−25.71[h]	−26.34	−25.72	17.79	18.44
Bicyclo[2.2.2]octane	−23.75[g]	−22.15	−24.22	12.95	11.23
endo-Tricyclo[5.2.1.$0^{2,6}$]decane	−14.38[g]	−12.31	−11.10	27.11	28.66
Adamantane	−30.65,[g] −30.57,[i] −32.96[j]	−32.50	−33.82	6.87	5.94
Diamantane	−36.64[k,l]	−37.37	−38.13	10.69	10.25
Cubane	+148.70	+148.59	+149.66	+165.87	+166.90

[a] Data from ref 1a unless otherwise noted. [b] Our calculations based on force field in Table III. [c] Our calculations based on force field described in ref 10a. See text for discussion. [d] Corrected to single conformation enthalpy, see P. v. R. Schleyer, J. E. Williams, and K. R. Blanchard, *J. Amer. Chem. Soc.*, 92, 2377 (1970). [e] Enthalpy based on estimated heat of vaporization or sublimation (see ref 1a for details), and therefore not included in the force field parameterization. [f] Enthalpy based on estimated heat of sublimation; see ref 10a for details, [g] Reference 20b. [h] M. P. Kozina, L. P. Timofeeva, S. M. Skuratov, N. A. Belikova, E. M. Milvitskaya, and A. F. Platé, *J. Chem. Thermodyn.*, **3**, 563 (1971). [i] R. S. Butler, A. S. Carson, P. G. Laye, and W. V. Steele, *ibid.*, **3**, 277 (1971). [j] M. Mansson, N. Rapport, and E. F. Westrum, Jr., *J. Amer. Chem. Soc.*, **92**, 7296 (1970). [k] A. S. Carson, P. G. Laye, W. V. Steele, D. E. Johnston, and M. A. McKervey, *J. Chem. Thermodyn.*, **3**, 915 (1971). [l] T. Clark, D. E. Johnston, H. Mackle, M. A. McKervey, and J. J. Rooney, *J. Chem. Soc., Chem. Commun.*, 1042 (1972).

In the parameterization of our force field model, we have attempted to choose potential functions to represent the strain components of eq 1 as much as possible from independent sources and then modify these when necessary in such a way as to maintain chemical and physical interpretability, while accomplishing the primary objectives of faithful reproduction of experimental structures and energies. To this end, initial force constants and potential functions for bond stretching and angle bending were taken from vibrational analysis;[7] while those describing torsional interactions were obtained from rotational barrier data (Table IV). Nonbonded potentials derived semiempirically to account for intermolecular interactions in crystalline hydrocarbons provided a starting point for evaluating intramolecular interactions.[23]

By a trail and error process, the parameters were successively modified to achieve an acceptable fit to the energies for the hydrocarbons in Table II, selected to represent a balanced set of diverse structural types. Most of the available experimental data are on simple acyclic alkanes. Inclusion of all these data would weigh the force field unduly toward these structural types.[10a] In Table II, a significant fraction of the available experimental enthalpies of cyclic, bicyclic, and polycyclic alkanes has been included in our force field parameterization along with a balanced representation of branched and unbranched structures. Our aim was to keep the force field as simple as possible, while still achieving good reproduction of the experimental data. Table III summarizes the potential functions and corresponding parameters that were finally settled upon, but it should be emphasized that there is nothing unique about these values, except that they work well. The rationale behind their choice follows.

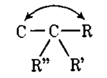
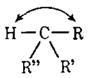
Table III. Molecular Force Field Used for Calculations on Alkanes[a]

Bond stretching $E(r) = 0.5k_r(r - r_0)^2$

Bond	k_r	r_0
C–H	4.6	1.100
C–C	4.4	1.520

Angle bending[b] $E(\theta) = 0.5k_\theta[\Delta\theta^2 - k_\theta'\Delta\theta^3]$ for $\Delta\theta \leq 25°$

$\Delta\theta = |\theta - \theta_0|$

Angle[c]	R	R'	R''	θ_0	k_θ
	C	C	C	109.5	0.57
	C	C	H	110.1	0.57
	C	H	H	110.4	0.57
	H	C	C	109.2	0.40
	H	C	H	109.0	0.40
	H	H	H	109.5	0.40
	H	C	C	109.1	0.33
	H	C	H	109.2	0.33

$k_\theta' = 0.55$

Torsional[d] $E(\phi) = 0.5k_\phi(1 + \cos 3\phi)$

Dihedral angle	$k_\phi \times 10^3$
HCCH	4.85
HCCC	4.85
CCCC	3.11

Nonbonded $E(d) = \dfrac{\epsilon}{1 - 6/\alpha}\left[\left(\dfrac{6}{\alpha}\, e^{\alpha(1 - r/r_m)}\right) - (r/r_m)^6\right]$

Nonbonded distance[e]	α	$\epsilon \times 10^4$	r_m
H···H	12.0	2.78	3.20
C···H	12.0	2.08	3.35
C···C	12.0	6.599	3.85

[a] All units are such that energies are in units of 10^{-11} ergs, angles in radians, and distances in ångstroms. To convert 10^{-11} erg molecule^{-1} to kcal/mol^{-1}, multiply by 144.0. [b] Absolute value of angle deformation employed. [c] Angles to be reduced to radians for use. [d] Rotational barriers are made up of an arbitrary combination of torsional and nonbonded strain components. That the CCCC force constant is smaller than the other torsional constants only reflects that this interaction is being weighed more in terms of nonbonded strain. [e] Modified Buckingham (6 − exp) potential where ϵ is the well depth, r_m the distance of the minimum, and α the steepness parameter. See J. O. Hirschfelder, C. F. Curtiss, and R. B. Bird, "Molecular Theory of Gases and Liquids," Wiley, New York, N. Y., 1954, p 33.

Force constants for stretching and bending were taken from the work of Snyder and Schachtschneider.[7] However, their bending constants overestimate angle strain even for relatively small deformations in bond angles (>5°). Reduced constants, in which the same proportionality has been maintained, are employed instead. In our attempts to incorporate the ability to evaluate small rings, it became apparent that reduction of the force constants to accommodate the strain in cyclobutane (angle deformation ~20°) results in strain underestimation in compounds with moderate angle deformations, *e.g.*, norbornane (angle deformations ~8–16°). To overcome this problem, a cubic term is subtracted from the typical harmonic potential (Table III). It should be noted that Allinger's force field[10a] also incorporates a cubic term in the angle bending function but in the opposite sense; that is, his cubic term adds to the quadratic term rather than subtracting from it. Boyd[20a] has criticized the use of a function that effectively results in having weaker force constants with increasing deformations in the bond angles. Instead, he treats cyclobutane as a separate electronic system with an assigned energy and geometry to be incorporated into larger systems. We claim no theoretical significance for our angle bending function, only that it achieves empirically a better representation for angle bending in strained molecules. We prefer this simpler approach of having one function capable of evaluating both small and large angle deformations, rather than adding to the complexity of the force field model by artificially treating four-membered rings as separate systems. The same approach could not be extended to three-membered rings, however (see discussion below).

The most crucial part of any parameterization is the choice of nonbonded potential functions. Yet, this is the area in which one of the more tenuous assumptions of the molecular mechanics method is made. Can nonbonded functions derived to describe intermolecular interactions be employed intramolecularly? We tested many possibilities, attempting to reproduce known energy differences in which nonbonded interactions are considered to play a major role. On this basis, the final choice is a further modified version[20] of the functions derived by Williams[24] to represent intermolecular interactions in crystalline hydrocarbons. Torsional constants were adjusted on the basis of experimental rotational barriers in ethane, propane, and *n*-butane (Table IV). Finally, preferred bond lengths (r_0) and bond angles (θ_0) were chosen in order to reproduce the experimental structures for propane and isobutane (Table V).

Table IV. Experimental and Calculated Torsional Barriers

	Torsional barriers (kcal/mol)		
		Calcd	
Compound	Exptl	Present study[a]	*Ab initio*[f,g]
Ethane	2.9[b]	2.8	3.3[f]
Propane	3.3[c]	2.9	3.7[f]
n-Butane	6.1,[d] 7.4[e]	5.8	7.0[g]

[a] Calculations based on force field described in Table III. [b] S Weiss and G. E. Leroi, *J. Chem. Phys.*, **48**, 962 (1968). [c] E. Hirota, C. Matsumura, and Y. Morino, *Bull. Chem. Soc. Jap.*, **40**, 1124 (1967). [d] Estimated value based on thermodynamic data on *n*-alkanes: K. Ito, *J. Amer. Chem. Soc.*, **75**, 2430 (1953). [e] Predicted value based on ultrasonic relaxation in 2-methylbutane: J. E. Piercy and M. G. S. Rao, *J. Chem. Phys.*, **46**, 3951 (1967). [f] L. Radom, W. J. Hehre, and J. A. Pople, *J. Amer. Chem. Soc.*, **94**, 2371 (1972). [g] L. Radom, W. A. Lathan, W. J. Hehre, and J. A. Pople, *ibid.*, **95**, 693 (1973).

Evaluation of Heats of Formation

From calculations based on eq 1, the geometry of a single minimum energy conformation of a molecule and the associated *steric energy* can be obtained. Such

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(24) (a) D. E. Williams, *J. Chem. Phys.*, **45**, 3770 (1966); (b) D. E. Williams, *ibid.*, **47**, 4680 (1967).

Table V. Experimental and Calculated Structural Parameters

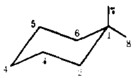
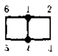
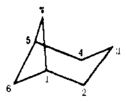
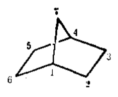
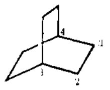
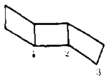
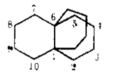
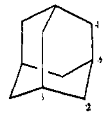
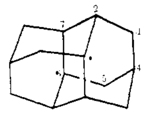
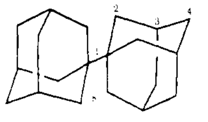
Alkane	Structural parameter	Exptl[a]	Calcd[b] Present study	Calcd[b] Allinger
Propane	r(CC)	1.533,[c,d] 1.532[e]	1.531	1.534
	θ(CCC)	112.4, 112.0	112.2	112.0
Isobutane	r(CC)	1.532,[c,f] 1.535[g]	1.532	1.532
	θ(CCC)	111.2, 110.8	110.7	111.1
Cyclobutane	r(CC)	1.548,[h] 1.568[i]	1.527	1.543
Cyclopentane	r(CC)	1.539,[h] 1.546[j]	1.528	1.534
	θ(CCH)	. . ., 111.7	111.0	111.3
Cyclohexane	r(CC)	1.528,[k] 1.528[l]	1.533	1.530
	θ(CCC)	111.0, 111.5	111.3	110.9
	ϕ(CCCC)	55.9, 54.5	55.3	56.4
Methylcyclohexane	r(CC) av	1.527[k]	1.533	1.530
	θ(CCC) ring	111.3	111.4	111.0
	θ(CCC) methyl	110.1	110.8	111.8
	ϕ(CCCC) av, ring	55.3	55.5	56.1
1,1-Dimethylcyclohexane	r(CC) av	1.533[m]	1.536	1.533
	$\theta(C_2C_1C_6)$	109.8	109.6	108.5
	$\theta(C_7C_1C_8)$	106.4	107.3	107.4
	$\theta(C_1C_2C_3)$	115.0	114.2	114.3
	$\theta(C_3C_4C_5)$	112.5	111.4	110.5
	$\phi(C_1C_2C_3C_4)$	51.3	53.9	55.5
	$\phi(C_2C_3C_4C_5)$	53.2	54.3	55.6
Bicyclo[2.2.0]hexane	$r(C_1C_2)$	1.557[n]	1.529	1.543
	$r(C_2C_3)$	1.542	1.526	1.541
	$r(C_1C_4)$	1.577	1.528	1.549
	$\theta(C_2C_1C_6)$	113.5	118.3	118.2
trans-Decalin	r(CC) av	1.537[o]	1.534	1.530
	θ(CCC) av	111.5	111.0	111.1
cis-Decalin	r(CC) av	1.536[o]	1.536	1.531
	θ(CCC) av	112.0	112.0	112.2
Bicyclo[3.1.1]heptane	$r(C_1C_2)$	1.511[p]	1.537	1.529
	$r(C_2C_3)$	1.534	1.543	1.541
	$r(C_1C_6)$	1.553	1.529	1.541
	$\theta(C_1C_2C_3)$	108.7	112.0	111.6
	$\theta(C_2C_3C_4)$	113.0	113.1	113.9
	$\theta(C_6C_1C_7)$	84.9	87.7	88.7
	$\theta(C_1C_6C_5)$	87.1	85.8	85.7
Norbornane	$r(C_1C_2)$	1.539,[q] 1.542,[r] 1.534,[s] 1.556[t]	1.533	1.535
	$r(C_2C_3)$	1.551, 1.543 1.578, 1.551	1.533	1.538
	$r(C_1C_7)$	1.560, 1.570, 1.535, 1.559	1.522	1.531
	$\theta(C_1C_7C_4)$	93.1, 93.2, 95.3, 96.0	93.3	93.1
	$d(C_1\cdots C_4)$	2.260, ..., ..., 2.317	2.21	2.22
Bicyclo[2.2.2]octane	$r(C_1C_2)$	1.538[u]	1.536	1.529
	$r(C_2C_3)$	1.552	1.540	1.533
	$\theta(C_1C_2C_3)$	109.7	110.1	109.5
	$d(C_1\cdots C_4)$	2.592	2.595	2.555
anti-Tricyclo[4.2.0.0^{2,5}]octane	r(CC) av	1.557[v]	1.527	1.542
	$\theta(C_1C_2C_3)$	111.9	117.4	117.3
syn-Tricyclo[4.2.0.0^{2,5}]octane	r(CC) av	1.566[v]	1.528	1.543
	$\theta(C_1C_2C_3)$	119.0	122.7	122.3
[4.4.4]Propellane	$r(C_1C_6)$	1.556[w,x]	1.561	1.539
	$r(C_1C_2)$	1.550	1.550	1.543
	$r(C_2C_3)$	1.531	1.534	1.534
	$r(C_3C_4)$	1.524	1.528	1.527
	$\theta(C_6C_1C_2)$	110.9	111.2	110.8
	$\theta(C_{10}C_1C_2)$	108.0	107.7	108.1
	$\theta(C_1C_2C_3)$	114.4	116.0	116.7
	$\theta(C_2C_3C_4)$	110.6	111.2	109.8
	$\phi(C_2C_1C_6C_5)$	48.8	46.7	46.3
	$\phi(C_6C_1C_2C_3)$	−52.3	−50.4	−51.3
Adamantane	r(CC) av	1.537[y]	1.537	1.528
	$\theta(C_1C_2C_3)$	110.0	110.0	109.2
	$\theta(C_2C_3C_4)$	109.2	109.2	109.6

Table V. (*Continued*)

Alkane	Structural parameter	Exptl[a]	Calcd[b] Present study	Calcd[b] Allinger
Diamantane	r(CC) av	1.535[w,z]	1.538	1.526
	$\theta(C_1C_2C_7)$	108.7	108.8	108.4
	$\theta(C_1C_2C_8)$	110.2	110.1	110.7
	$\theta(C_2C_3C_4)$	110.2	110.0	109.0
	$\theta(C_3C_4C_5)$	108.8	109.1	109.5
1,1′-Biadamantane	$r(C_1C_{1'})$	1.578[aa]	1.583	1.575
	$r(C_1C_2)$	1.546	1.552	1.540
	$r(C_2C_3)$	1.536	1.537	1.531
	$r(C_3C_4)$	1.529	1.533	1.526
	$\theta(C_1{}'C_1C_2)$	111.7	112.7	113.5
	$\theta(C_8C_1C_2)$	107.2	106.0	105.2
	$\theta(C_1C_2C_3)$	111.6	113.2	114.0
	$\theta(C_2C_3C_4)$	109.6	109.4	109.7
	$\theta(C_3C_4C_5)$	109.2	109.2	108.1

[a] Gas-phase electron diffraction data unless otherwise noted. Distances are reported in ångstroms, and angles in degrees. Data referencing follows order for the first structural entry of each compound. [b] Our calculations based on the force field models described in Table III and ref 10a. [c] Microwave data corrected to electron diffraction results by adding 0.07 Å to C–C bond length; see D. R. Lide, Jr., *Tetrahedron*, **17**, 125 (1962). [d] D. R. Lide, Jr., *J. Chem. Phys.*, **33**, 1514 (1960). [e] T. Iijima, *Bull. Chem. Soc. Jap.*, **45**, 1291 (1972). [f] D. R. Lide, Jr., *J. Chem. Phys.*, **33**, 1519 (1960). [g] R. L. Hilderbrandt and J. D. Wieser, *J. Mol. Struct.*, **15**, 27 (1973). [h] A. Almenningen, O. Bastiansen, and P. N. Skancke, *Acta Chem. Scand.*, **15**, 711 (1961). [i] J. D. Dunitz and V. Schomaker, *J. Chem. Phys.*, **20**, 1703 (1952). [j] W. J. Adams, H. J. Geise, and L. S. Bartell, *J. Amer. Chem. Soc.*, 92, 5013 (1970). [k] H. J. Geise, H. R. Buys, and F. C. Mijlhoff, *J. Mol. Struct.*, **9**, 447 (1971). [l] M. Davis and O. Hassel, *Acta Chem. Scand.*, **17**, 1181 (1963). [m] H. J. Geise, F. C. Mijlhoff, and C. Altona, *J. Mol. Struct.*, **13**, 211 (1972). [n] B. Andersen and R. Srinivasan, *Acta Chem. Scand.*, **26**, 3468 (1972). [o] M. Davis and O. Hassel, *Acta Chem. Scand.*, 18, 813 (1964). [p] G. Dallinga and L. H. Toneman, *Recl. Trav. Chim. Pays-Bas*, 88, 185 (1969). [q] A. Yokozeki and K. Kuchitsu, *Bull. Chem. Soc. Jap.*, **44**, 2356 (1971). [r] Y. Morino, H. K. Kuchitsu, and A. Yokozeki, *ibid.*, **40**, 1552 (1967). [s] G. Dallinga and L. H. Toneman, *Recl. Trav. Chim. Pays-Bas*, 87, 795 (1968). [t] J. F. Chiang, C. F. Wilcox, Jr., and S. H. Bauer, *J. Amer. Chem. Soc.*, 90, 3149 (1968). [u] A. Yokozeki, K. Kuchitsu, and Y. Morino, *Bull. Chem. Soc. Jap.*, **43**, 2017 (1970). [v] B. Andersen and L. Fernholt, *Acta Chem. Scand.*, **24**, 445 (1970). [w] X-Ray diffraction data on solid. [x] O. Ermer, R. Gerdil, and J. D. Dunitz, *Helv. Chim. Acta*, **54**, 2476 (1971). [y] I. Hargittai, *Chem. Commun.*, 1499 (1971). [z] I. L. Karle and J. Karle, *J. Amer. Chem. Soc.*, 87, 919 (1965). [aa] R. A. Alden, J. Kraut, and T. G. Traylor, *ibid.*, **90**, 74 (1968).

steric energies are raw numbers, but may be used directly to obtain energy differences between stereoisomers and isologous molecules (*i.e.*, isomers differing in connectivity but possessing the same number of different kinds of groups (CH_3, CH_2, CH, C, etc.)). The energy difference between boat and chair conformations of cyclohexane, the cis and trans isomers of 1,4-dimethylcyclohexane, and ethylcyclopentane and methylcyclohexane provide examples where steric energies are applicable directly. Heats of formation are required for other types of energy comparisons.

The energies calculated by eq 1 in principle are appropriate to molecules in a *hypothetical motionless state* at 0°K.[20a] Corrections for the chemical binding energy, the vibrational zero point energy, and the thermal energy of translation, rotation, and vibration (as well as errors inherent in the parameterization) have to be made in order to convert steric energies to heats of formation in the gas phase at 25°.[9,20a,25,26] We have adopted the simplest approach of assuming additivity of these terms and have derived group increments based on a least-squares optimization of the calculated steric energies from eq 1 with the experimental heats of formation at 25° for the compounds listed in Table II. Allinger and coworkers[10a] have treated the problem similarly, but used bond, rather than group, additivities. Both schemes are mutually consistent and we have converted their bond increments to group increments in Table VI for comparison purposes.

Zero-point and thermal energies, which represent the total kinetic energy and potential energy of vibration of the molecule, depend only on molecular modes of vibration, rotation, etc., and would not necessarily be expected to be additive properties.[9,20a,25,26] Boyd and coworkers[20a] evaluated these energies by employing the vibrational frequencies calculated with their force field. The results obtained indicated that zero-point and thermal energies follow group additivity for normal and branched alkanes but not for strained cyclic and polycyclic systems. However, the reliability of frequencies calculated for strained systems are questionable since only simple unstrained acyclic and cyclic structures were employed in their force field parameterization. In view of the almost total lack of firm experimental data concerning the magnitudes of zero-point and thermal energy contributions to the enthalpy and the numerous simplifying assumptions already implicit in the molecular mechanics method, we prefer to assume additivity which certainly is more convenient. In fact, deviations from additivity in the zero-point and

Table VI. Group Increment Steric Energy Corrections

Force field	CH_3	CH_2	CH	C
	General Increment[a]			
Present study[b]	−10.82	−5.88	−2.82	−0.82
Allinger[c]	−11.18	−5.97	−0.75	+4.17
	Strainless Increment[d]			
Present study[e]	−10.05	−5.13	−2.16	−0.30
Allinger[c]	−10.00	−5.19	−2.16	−0.22

[a] Group increments to correct steric energies from eq 1 to heats of formation, gas phase at 25°. [b] Derived from calculations based on force field in Table III. [c] Group increments derived from bond increments in ref 10a. [d] Strain-free group increments to be subtracted from heats of formation to give strain energies, gas phase, 25°. [e] Single conformation strain-free group increments derived by P. v. R. Schleyer, J. E. Williams, and K. R. Blanchard, *J. Amer. Chem. Soc.*, **92**, 2377 (1970).

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(25) T. L. Cottrell, *J. Chem. Soc.*, 1448 (1948).

(26) M. J. S. Dewar, *Trans. Faraday Soc.*, **42**, 767 (1946).

thermal energies for strained compounds are indirectly compensated by the modifications of the force field parameters to fit these systems.

Energy Minimization

In order for consistent and credible calculated results to be obtained, a reliable minimization procedure is necessary. The many problems associated with this aspect of molecular mechanics have already been discussed.[2] We have employed a variety of energy minimization routines (*e.g.*, steepest descent[2] and parabolic prediction, a method based on quadratic expansion of the potential surface near the minimum) and have found a modified pattern-search method of Hooke and Jeeves[27] to work extremely well in moving along the potential energy surface of the molecule to the point of lowest energy.

Energy minimization schemes cannot be made to avoid false minima entirely. This problem is particularly acute when movement to the energy minimum requires, in effect, twisting around torsional angles in a molecule. Bond lengths and bond angles optimize rapidly in the initial stages of minimization, and some torsional movement occurs during the initial iterations. However, once bond lengths and bond angles have reached equilibrium values, further torsional movement is inhibited, since additional lowering of the total energy requires the coupled movement of several atoms. Furthermore, when torsional angles are near 0 or 60°, the usual cosine torsional potential is very flat, and movement here does not lower the energy sufficiently to compensate for the distortions in bond lengths and bond energies. For example, eclipsed ethane does not minimize to its more stable staggered conformation unless special actions are taken, such as changing the shape of the torsional potential[28] or including routines that enable movement of the three hydrogens on the methyl group in a concerted manner.[29]

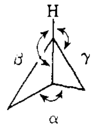
Polycyclic molecules with two-carbon bridges illustrate a related problem in energy minimization.[23a] In many of these systems, no unique minimum energy geometry was found, rather a number of conformations with closely similar energies. This indicates the presence of broad potential wells, retarding movement along the energy surface during minimization. Hence, it is necessary to input a number of trial geometries in which the torsional angles in the CCH_2CH_2C bridges are varied in order to probe the energy surface correctly.

While one cannot be completely certain that a false minimum has not been reached, we have attempted to reduce this possibility by employing a variety of starting geometries when flexible molecules were being considered. This approach has been facilitated greatly through access to an interactive graphics conformational analysis program developed by Wipke and coworkers[28] at Princeton. This program provided us with initial trial Cartesian coordinates. Furthermore, three-dimensional display of the structures provided a direct, visual check that the desired conformation had been obtained.

Limitations of the Force Field Model

The success of molecular mechanics calculations depends on the ability of the model to approximate the systems under consideration. One of the basic assumptions of the method is that potential energy functions, particularly angle bending, applicable to relatively unstrained systems are transferable to more strained compounds. This assumption becomes less tenable as one moves farther from "normal" alkane structures; therefore, it is not surprising that three- and four-membered ring data are not reproduced well by the usual alkane force fields. In the present treatment, three-membered rings have been excluded (and will eventually be considered as a separate functional group). Because of their exceptional 60° internuclear bond angles, cyclopropanes do not display usual alkane behavior. Four-membered rings exhibit similar tendencies, but to a much less extent. Only minor adjustment in the angle bending function was necessary to accommodate the ~20° deformation from normal bond angles encountered in four-membered rings, but it is very difficult to treat in any consistent way the strain energy resulting from the 50° distortion found for cyclopropane. Thus, the bond angles experimentally determined for cyclopropyl-containing compounds do not correspond to the minimum energy conformations calculated on the basis of our standard preferred alkane bond energies. For example, the experimental bridgehead angles in bicyclobutane (Table VII) display much larger angle deformations than the calculated values. It appears that different equilibrium parameters are needed to account adequately for these structural features.

Table VII. Experimental and Calculated Bond Angles (deg) for Bicyclo[1.1.0]butane



	Exptl[a]		Calcd[c]	
Bond angle	Angle θ	Deformation[b] $\lvert\theta - \theta_0\rvert$	Angle θ	Deformation $\lvert\theta - \theta_0\rvert$
α	98.3	11.8	111.4	1.3
β	128.4	19.2	109.3	0.1
γ	130.4	21.2	113.7	4.5

[a] K. W. Cox and M. D. Harmony, *J. Chem. Phys.*, **50**, 1976 (1969). [b] Bond angle distortion from normal or strain-free angle given in Table III. [c] Calculations based on force field described in Table III.

Another limitation of force field models arises from the fact that molecular mechanics is basically an empirical method. It is applicable to compound classes where adequate experimental data are available to allow parameterization. While considerable experimental data are available for structures with angle deformations up to about 20° from normal values, no experimental enthalpies are available for systems with deformations outside this range, except for compounds containing three-membered rings. Therefore, molecular mechanics calculations cannot be expected to be reliable for molecules with angle deformations between

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(27) R. Hooke and T. A. Jeeves, *J. Ass. Computing Machinery*, **8**, 212 (1961).

(28) W. T. Wipke, P. Gund, J. Verbalis, and T. Dyott, unpublished work.

(29) J. D. Andose, unpublished work.

Table VIII. Experimental and Calculated Structures for Cyclodecane

Structural parameter	Exptl[a]	Calcd						
		Present study[b,c]	Allinger[b,d]	Boyd[b,e]	Bixon and Lifson[f,g]	Wiberg[h,i]		Hendrickson[f,i,k]
						Set 1	Set 2	
θ_{av}(CCC)	117	118	118	116	116	116	115	117
ϕ_1	55	55	55	55	54	53	51	55
ϕ_2	−152	−149	−148	−153	−151	−152	−149	−152
ϕ_3	55	55	55	55	53	52	51	55
ϕ_4	66	65	65	67	70	72	71	66
ϕ_5	−66	−65	−65	−67	−68	−67	−71	−66
ϕ_6	−55	−55	−55	−54	−56	−57	−51	−55
ϕ_7	152	149	148	153	153	153	149	152
ϕ_8	−55	−55	−54	−55	−53	−60	−51	−55
ϕ_9	−66	−65	−65	−67	−71	−61	−71	−66
ϕ_{10}	66	65	65	67	71	66	71	66

[a] Parameters derived from five X-ray determinations on substituted cyclodecanes for an "averaged" ring of C_{2h} symmetry (ref 30). [b] No symmetry restrictions during minimization. [c] Our calculations based on force field in Table III. [d] Our calculations using force field described in ref 10a. [e] Our calculations using force field described in ref 20a. [f] Local C_{2v} symmetry of methylene groups preserved during minimization. [g] Calculations from ref 9b. Only H···H nonbonded interactions considered. [h] Calculations from ref 6. [i] C_{2h} symmetry assumed for ring. [j] Repulsive C···C and C···H nonbonded interactions not considered. [k] Calculations from ref 5b.

Table IX. Experimental and Calculated Structural Parameters for Tri-*tert*-butylmethane

Parameter[a]	Expt[b]	Calcd				
		Present study	Allinger[c]	Boyd[d]	CFF3[e]	JTB[f]
C–H	1.111	1.098	1.091	1.088	1.100	1.112
C_t–C_q	1.611	1.592	1.587	1.601	1.569	1.595
C_q–C_m	1.548	1.544	1.549	1.549	1.528	1.552
θ $H_tC_tC_q$	101.6	99.8	98.6	101.9	100.9	102.4
θ $C_qC_tC_q$	116.0	117.2	117.8	115.9	116.5	115.5
θ $C_tC_qC_m$	113.0	114.6	114.5	113.3	114.7	112.5
θ $C_mC_qC_m$	105.8	104.1	104.0	105.3	103.8	106.2
θ $C_qC_mC_m$	114.2	113.0	113.5	111.6	111.4	112.4
$\Delta\phi$ $H_tC_tC_qC_m$	10.8	15.0	15.0	15.5	16.4	15.8

[a] Averaged values. Subscripts: t = tertiary, q = quaternary, m = methyl. [b] H. B. Burgi and L. S. Bartell, *J. Amer. Chem. Soc.*, **94**, 5236 (1972). [c] Our calculations based on the force field described in ref 10a. [d] Our calculations based on force field described in ref 20a. [e] Calculations from ref 31 employing force field described in ref 9a. [f] Calculations from ref 31 employing force field described in ref 8.

~20 and ~50°. In the present force field model, we have arbitrarily set a 25° angle deformation as the limit of our bending function and have eliminated from consideration molecules with distortions greater than this value.

Calculation of Structures by the Molecular Mechanics Method

The early applications of molecular mechanics primarily dealt with the evaluation of the preferred geometries of the medium-ring cycloalkanes. Since Hendrickson's work in this area, a number of additional studies of varying degrees of sophistication have appeared.[5,6,9,10a] The calculated structures are, for the most part, remarkably consistent despite the wide variety of force field models employed. Cyclodecane, a molecule of considerable complexity, provides an illustrative example. The results of five X-ray diffraction studies on differently substituted cyclodecane derivatives indicated that the ring seems to prefer a single boat–chair–boat (BCB) conformation.[30] The "average" structure from these determinations assuming mirror symmetry for the ring is summarized in Table VIII along with the calculated structural parameters for the BCB conformation using seven different force fields. The agreement between experimental and calculated structures is noteworthy.

Recently, the possibility of an even more rigorous test of the ability of molecular mechanics to calculate accurately the structure of a complex organic molecule was provided by the electron diffraction study by Bartell and Burgi[31] on tri-*tert*-butylmethane, a molecule suffering from considerable steric crowding. Table IX summarizes the experimental structural parameters for this molecule, along with the values calculated using five different force field models. The good agreement between experimental and calculated structures in Table IX seems even more remarkable when one considers that no experimental structures possessing a similar extent of steric congestion as encountered in tri-*tert*-butylmethane were available for the parameterization of these force fields. The results of Tables VIII and IX demonstrate the potential and the reliability of the molecular mechanics method in determining structures. Moreover, the structures calculated do not appear to be a sensitive function of the force field employed. Good results are obtainable even with rather simple force fields. The force field of Bixon and Lifson[9b] (*cf.*, *e.g.*, Table VIII) achieves excellent agreement for the whole series of medium-ring cycloalkanes from C_5 through C_{12} even though C···C and C···H nonbonded interactions were neglected.

Molecular mechanics is able to calculate the geometries of a wide range of molecules remarkably well. Table V summarizes most of the available structural data on alkanes, together with calculated values based on our force field model and that of Allinger and co-

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(30) J. D. Dunitz, *Perspect. Struct. Chem.*, **2**, 1 (1969).

(31) L. S. Bartell and H. B. Burgi, *J. Amer. Chem. Soc.*, **94**, 5239 (1972).

Table X. Experimental and Calculated Relative Strain Energies for Cycloalkanes

Ring	Relative strain energies[a]							
		Calcd						
						Wiberg[k]		
size *n*	Exptl[b]	Present study[f]	Allinger[g]	Boyd	CFF[j]	Set 1	Set 2	Hendrickson[l]
5	6.14	6.09	6.85	6.35[h]	7.3			
6	0	0	0	0	0	0	0	0
7	6.20	5.98	6.42	5.95[h]	6.8			6.0
8	9.60	9.97	10.65	10.30[h]	10.1	10.4	11.0	10.0
9	(12.45)[c]	13.31	13.66		12.2			12.9
10	(12.87)[c]	13.98	12.48	12.90[i]	12.2	12.2	10.1	13.2
11	(11.21)[c]	12.68	11.61		13.2			
12	(3.97),[d] (8.49)[e]	8.74	7.42	7.80[i]	4.8	3.2	2.1	

[a] Strain energies relative to cyclohexane evaluated using eq 2. [b] Data taken from ref 1a. [c] Heat of formation based on estimated heat of vaporization; see ref 1a for details. [d] Heat of formation based on estimated heat of sublimation; see ref 1a for details. [e] Heat of formation based on estimated heat of sublimation; see ref 10a for details. [f] Our calculations based on force field in Table III. [g] Our calculations based on force field described in ref 10a. [h] Calculations from ref 20. [i] Our calculations for cyclodecane and cyclododecane using Boyd's force field (ref 20a). [j] Calculations from ref 9f. [k] Calculations from ref 6. [l] Calculations from ref 5b.

workers.[10a] In fact, the calculations are so good that any evaluation of their accuracy must take the precision achievable by the experimental methods into account. In short, the experimental data may be no more accurate than that obtained by force field calculations. The majority of the experimental structures in Table V have been determined by gas-phase electron diffraction. For the most part, these results are considered reliable in favorable instances to about 0.01 Å in bond lengths and 1–2° in bond and torsional angles. This precision is somewhat less for larger and less symmetrical molecules where simplifying assumptions may enter into the refinement of the data. By this criterion, most of the calculated structures in Table V achieve an accuracy rivaling the precision of the experimental determinations. Types of compounds where discrepancies are observed illustrate insufficiencies of the simplified force field employed here. For example, in small caged systems such as norbornane or in molecules incorporating four-membered rings the carbon–carbon bond lengths consistently are calculated to be shorter than those found experimentally. This deficiency is the result of not explicitly considering 1,3 nonbonded interactions in our force field. Inclusion of such 1,3 interactions and the use of an anharmonic bond-stretching function has been shown to lead to somewhat better results for molecules of this type.[19,31] Allinger has attempted to deal with this problem in a different way.[10a] A bend–stretch interaction potential was included in his force field in order to account for the increase in bond lengths along the series cyclohexane, cyclopentane, cyclobutane. This bend–stretch potential, however, does not reproduce the bond length variation in molecules such as norbornane (Table V). While these additional terms lead to slightly better agreement with some experimental bond lengths, the use of a simple harmonic bond-stretching potential appears to be adequate for general use. For example, the observed variations in carbon–carbon bond lengths in [4.4.4]propellane and 1,1′-biadamantane are reproduced well by our calculations using just a simple haromic bond-stretching potential. Furthermore, the often minor improvements (0.01–0.02 Å) in bond lengths realized by adding additional terms is overshadowed by the rather large experimental uncertainties which become apparent when several determinations on the same molecule are compared. For example, four structural determinations on norbornane have appeared recently in the literature with discrepancies as large as 0.03 Å in bond lengths (Table V).

The largest deviations (~5°) of the calculated from the experimental angles (Table V) occurs for bicyclo[2.2.0]hexane and *anti*-tricyclo[4.2.0.0^{2,5}]octane at the junction of the four-membered rings where the bonds are strained appreciably. The assumption that the normal alkane structural parameters can adequately describe the strain around these centers begins to break down. Related molecules, such as *syn*-tricyclo[4.2.0.0^{2,5}]octane and bicyclo[3.1.1]heptane, are estimated somewhat better with deviations around 3° in bond angles. Of course, concern about the accuracy of the experimentally determined structures is a factor in these cases as well.

The agreement between the structures calculated using the two force fields (Table V) is representative of that achieved for all of the molecules listed in Tables II and XII. Since it would be impractical and unnecessary to reproduce here all of these structural data, they are presented elsewhere in the form of minimized Cartesian coordinates, from which all other structural parameters can be obtained.[32]

Calculation of Energies by the Molecular Mechanics Method

Cycloalkanes represent one of the few classes of molecules for which direct comparisons of the ability of various force field models to calculate energies are possible. The majority of the literature force fields have not been parameterized to evaluate heats of formation and are restricted to comparisons of energies between conformational isomers or between isologous compounds (see above). Strain energy in the homologous series of cycloalkanes is expressed conveniently relative to the energy of cyclohexane by eq 2 where n

$$\text{relative strain} = \Delta H_f°(n) - \Delta H_f°(\text{cyclohexane})(n/6) \quad (2)$$

equals the ring size. Table X summarizes the experimental strain energies evaluated by eq 2 for the C_5–C_{12}

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(32) E. M. Engler, Ph.D. Thesis, Princeton University, 1973. Calculated Cartesian coordinates for compounds listed in Tables II and XII using the force field described in Table III will appear in the microfilm edition of this volume of the journal. See paragraph at end of paper regarding supplementary material.

cycloalkanes, along with the relative energies calculated using seven different force fields. In general, good agreement (within 1 kcal/mol) between experimental and calculated values is observed for most of the cycloalkanes. That seven different force fields can reproduce the cycloalkane energies so precisely does not necessarily imply that these force fields can be applied with confidence to other, structurally different systems. The good agreement may be misleading. In any calculation method, better agreement is generally realized when relative values in a series of related systems are compared since absolute defects in the method tend to cancel. Only the first three force field models in Table X (present study, Allinger,[10a] and Boyd[20a]) have been applied to a wide variety of structurally diverse systems.

While experimental heats of combustion are available for all of the cycloalkanes in Table X, heats of vaporization, ΔH_v (or sublimation, ΔH_s), needed to obtain heats for formation in the gas phase at 25° are only available for C_5–C_8 ring systems. Enthalpies for cycloalkanes C_9–C_{11} are based on estimated heats of vaporization using Fishtine's method[1a] and can be considered no more reliable than ±1 kcal/mol. While many schemes are available for estimating ΔH_v, little information is available for calculating ΔH_s.[1a] Two estimates, differing by some 5 kcal/mol, have appeared in the literature for the heat of sublimation of cyclododecane.[1a,10a] Recourse to molecular mechanics calculations on this molecule in Table X finds support for *both* estimates. The force field of Wiberg[6] and of Lifson and Warshel[9b] indicate strains of 3.0 and 4.8 kcal/mol, respectively, relative to cyclohexane. The good agreement among the more extensively tested force field models (present study, Allinger,[10a] and Boyd[20a]) strongly favors the higher strain estimate of about 8.0 kcal/mol for cyclododecane.

How well do the various force fields reproduce the experimental heats of formation? A summary is provided in Table II for our force field model and that of Allinger and coworkers.[10a] That we have correctly incorporated Allinger's force field into our program was checked by repeating many of his calculations.[10a] In most cases, agreement was within 0.2 kcal/mol, with our values consistently lower (less strained). The largest discrepancies (~1 kcal/mol) were noted for the medium-ring cycloalkanes (C_9, C_{10}, and C_{12}). Again, our calculations using Allinger's force field model gave more negative heats of formation. These differences appear attributable to our employing a more efficient minimization routine and complete relaxation of symmetry constraints during minimization. For cyclodecane, Allinger and coworkers[10a] report the enthalpy only for the BCB conformation (Table VIII); however, our calculation using their force field found a twisted chair–chair–chair conformation (TCCC) to be about 1.8 kcal/mol more stable (see Table XIV and discussion below).

Both force fields reproduce the known enthalpy data of Table II equally well. The standard deviation between experimental and calculated values are 0.83 kcal/mol for our force field and 1.03 kcal/mol for Allinger's model. The average claimed experimental error for the set of alkanes in Table II is 0.49 kcal/mol. These errors, however, reflect the precision of the individual determinations and not the absolute accuracy. Larger discrepancies in experimental enthalpies are often noted for the more complex systems when several independent measurements are available. For example, the experimental determinations of the heat of formation for adamantane differ by some 2 kcal/mol (Table II).

While the known experimental data appear to be reproduced adequately, the reliability of these force fields in predicting heats of formation of systems which may possess structural features not encountered in the set of molecules in Table II remains to be established. The large number of adjustable parameters in molecular mechanics force fields enable different parameter sets to reproduce equally well the limited experimental enthalpy data. Each parameter set represents a different blend of strain components of eq 1. For example, the strain components calculated by three force field models for tri-*tert*-butylmethane in Table XI vary considerably.

Table XI. Calculated Strain Components for Tri-*tert*-butylmethane (kcal/mol)

	Force field		
Strain component	Present study[a]	Allinger[b]	Boyd[c]
Bond stretch	6.72	9.52	5.89
Angle bending	19.39	21.09	13.88
Torsional	2.74	2.59	3.13
Nonbonded	20.76	1.89	17.50
Bend-stretch[b]		−3.60	
Total steric energy	49.61	31.48	40.40
General group contributions[d]	−102.69[e]	−88.85[e]	−96.20[f]
ΔH_f° (gas, 25°)	−53.08	−57.37	−55.80

[a] Calculations based on force field in Table III. [b] Our calculation using force field described in ref 10a. [c] Our calculation using force field described in ref 20a. [d] See text for discussion. [e] Calculated from general group increments in Table VI. [f] Calculated from values given in ref 20a.

The total steric energies from eq 1 differ by nearly 19 kcal/mol between our force field and Allinger's yet, when the general group increment contributions (Table VI) are added to the steric energies, the calculated enthalpies differ only by 4 kcal/mol. While the close agreement between the three force fields in Table XI in predicting the enthalpy of such a complex molecule is encouraging, it would *not* be expected that the different blends of strain components and group contributions would always balance out when tested over a wide range of molecules.

We investigated this problem by carrying out calculations on an extensive number of alkanes, summarized in Table XII. Highly congested and strained polycyclic systems were emphasized in order to encounter the widest variety of novel structural situations. Although agreement between the force fields does not necessarily indicate that the enthalpy is being correctly evaluated, it does increase confidence in the calculated result. Further, large discrepancies between calculated values should provide insights into difficulties in the force field models that were not apparent from consideration of the available experimental data (Table II).

Since many of the experimental heats of formation on polycyclic alkanes are reported with error limits of about 1–2 kcal/mol, agreement within 2 kcal/mol was

Table XII. Calculated Enthalpies and Strain Energies for Alkanes (kcal/mol)

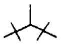
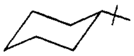
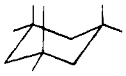
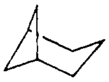
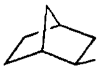
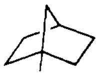
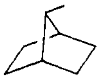
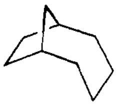
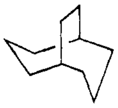
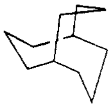
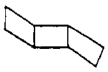
Alkane	Structure	Calcd ΔH_f° (gas, 25°)			Calcd Strain (gas, 25°)[d]	
		Present study[a]	Allinger[b]	Diff[c]	Present study[a]	Allinger[b]
2,2,3,4,4-Pentamethylpentane		−58.07	−60.43	1.36	15.04	12.18
tert-Butylcyclohexane		−52.82	−53.77	0.95	5.44	4.57
1,1,3,3,5,5-Hexamethylcyclohexane		−65.17	−64.04	−1.13	11.42	12.28
cis-Bicyclo[2.2.0]hexane		25.83	27.20	−1.37	50.67	52.27
Bicyclo[2.1.1]hexane		16.37	19.18	−2.81	41.21	44.25
Bicyclo[3.2.0]heptane		0.51	4.13	−3.62	30.48	34.39
Bicyclo[3.1.1]heptane		5.88	5.24	0.64	35.85	35.50
exo-2-Methylbicyclo[2.2.1]heptane		−20.01	−19.94	−0.07	17.04	17.24
endo-2-Methylbicyclo[2.2.1]heptane		−19.15	−19.10	−0.05	17.90	18.11
1-Methylbicyclo[2.2.1]heptane		−22.55	−22.78	0.23	15.61	15.59
1-Methylbicyclo[2.2.1]heptane		−18.28	−18.78	0.50	18.77	18.43
Bicyclo[3.2.1]octane[e]		−23.04	−24.22	1.16	12.06	11.24
Bicyclo[4.2.1]nonane[e]		−19.28	−18.28	−1.00	20.95	22.36
Bicyclo[3.3.1]nonane[e]		−30.64	−30.37	−0.27	9.59	10.28
Bicyclo[3.2.2]nonane[f]		−24.82	−25.40	0.58	15.41	15.24
Bicyclo[3.3.2]decane[f]		−26.17	−25.20	−0.97	19.19	20.63
Bicyclo[3.3.3]undecane (manxane)[g]		−25.21	−22.81	−2.40	25.28	28.21
anti-Tricyclo[4.2.0.0^{2,5}]octane		45.39	48.97	−3.58	74.55	78.35
syn-Tricyclo[4.2.0.0^{2,5}]octane		50.29	53.16	−2.87	79.45	82.54

Table XII (*Continued*)

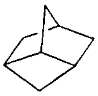
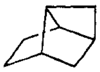
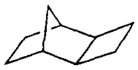
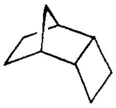
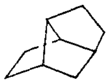
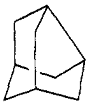
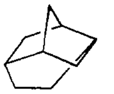
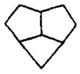
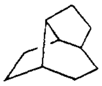
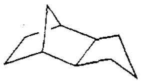
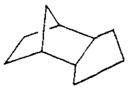
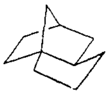
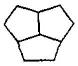
Alkane	Structure	Calcd ΔH_f° (gas, 25°) Present study[a]	Allinger[b]	Diff[c]	Calcd Strain (gas, 25°)[d] Present study[a]	Allinger[b]
Tricyclo[3.2.1.0^{3,6}]octane		12.30	13.05	−0.75	41.46	42.43
Tricyclo[3.3.0.0^{2,7}]octane		19.13	23.11	−3.98	48.29	52.49
Tricyclo[3.3.0.0^{3,7}]octane (bisnoradamantane)[h]		17.99	16.17	1.82	47.15	45.55
exo-Tricyclo[4.2.1.0^{2,5}]nonane		8.22	8.28	−0.06	42.51	42.85
endo-Tricyclo[4.2.1.0^{2,5}]nonane		13.04	13.58	−0.54	47.33	48.15
Tricyclo[4.2.1.0^{3,7}]nonane (brendane)[i]		−11.72	−10.31	−1.41	22.57	24.26
Tricyclo[4.3.0.0^{3,7}]nonane (brexane)[i]		−8.82	−9.10	0.28	25.47	25.47
Tricyclo[3.3.1.0^{3,7}]nonane (noradamantane)[j]		−14.22	−15.49	1.27	20.07	19.08
Tricyclo[4.3.0.0^{3,8}]nonane		−0.12	−3.87	3.75	34.17	30.70
Tricyclo[4.2.1.0^{4,9}]nonane (norperhydroquinacene)		1.99	5.56	−3.57	36.28	40.13
Tricyclo[5.3.0.0^{4,10}]decane[k]		−18.68	−19.45	0.77	20.74	20.31
exo-Tricyclo[5.2.1.0^{2,6}]decane[k]		−16.77	−15.90	−0.87	22.65	23.86
trans-Tricyclo[5.2.1.0^{2,6}]decane[l]		2.23	1.25	0.98	41.65	41.01
exo-Tricyclo[5.2.1.0^{1,5}]decane[k]		−16.85	−16.73	−0.12	23.68	24.19
endo-Tricyclo[5.2.1.0^{1,5}]decane[k]		−9.38	−10.41	1.03	31.15	30.51
Tricyclo[5.2.1.0^{3,8}]decane[k]		−20.16	−19.74	−0.48	19.26	20.08
Tricyclo[5.2.1.0^{4,10}]decane[k] (perhydroquinacene)		−23.74	−19.74	−4.00	15.68	20.02

Table XII (*Continued*)

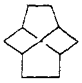
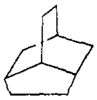
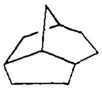
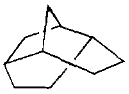
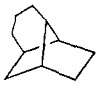
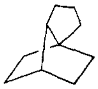
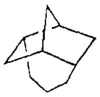
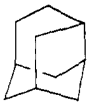
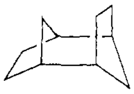
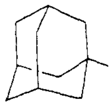
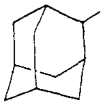
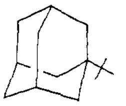
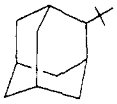
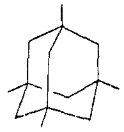
Alkane	Structure	Calcd $\Delta H_f°$ (gas, 25°): Present study[a]	Allinger[b]	Diff[c]	Calcd Strain (gas, 25°)[d]: Present study[a]	Allinger[b]
Tricyclo[4.4.0.$0^{3,8}$]decane[a] (twistane)		−13.30	−21.87	8.57	26.12	17.89
Tricyclo[4.3.1.$0^{3,7}$]decane[k] (isotwistane)		−18.65	−19.28	0.63	20.77	20.48
Tricyclo[5.2.1.$0^{4,8}$]decane[k]		−17.94	−17.30	−0.64	21.48	22.46
Tricyclo[4.4.0.$0^{3,9}$]decane[k]		−8.52	−12.44	3.92	30.90	27.32
Tricyclo[4.4.0.$0^{3,7}$]decane[k]		−15.83	−16.33	0.50	23.59	23.43
Tricyclo[4.2.2.$0^{1,5}$]decane[k]		−10.88	−11.98	1.10	29.65	28.94
Tricyclo[5.3.0.$0^{3,9}$]decane[k]		−6.60	−8.48	1.88	32.82	31.28
Tricyclo[4.3.1.$0^{3,8}$]decane (protoadamantane)[k]		−21.13	−22.63	1.50	18.29	17.13
syn-Tricyclo[4.2.1.$1^{2,5}$]decane[k]		0.96	−1.48	2.54	40.38	38.28
anti-Tricyclo[4.2.1.$1^{2,5}$]decane[k]		−8.76	−12.70	3.94	30.66	27.06
1-Methyladamantane[n]		−41.82	−42.89	1.07	5.79	4.98
2-Methyladamantane[n]		−37.94	−39.04	1.10	8.56	7.67
1-*tert*-Butyladamantane[o]		−53.41	−55.37	1.96	14.60	12.75
2-*tert*-Butyladamantane[o]		−50.65	−52.47	1.82	16.25	14.49
1,3,7,9-Tetramethyladamantane[p]		−70.26	−70.21	−0.05	1.92	1.99

Table XII (*Continued*)

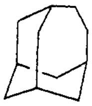
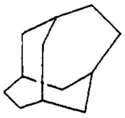
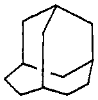
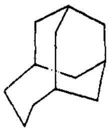
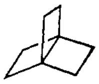
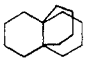
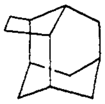
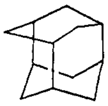
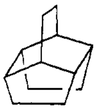
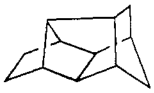
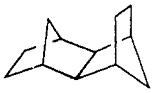
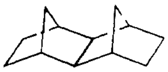
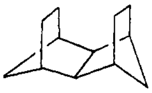
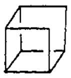
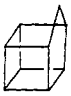
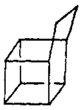
Alkane	Structure	Calcd ΔH_f° (gas, 25°) Present study[a]	Calcd ΔH_f° (gas, 25°) Allinger[b]	Calcd ΔH_f° (gas, 25°) Diff[c]	Calcd Strain (gas, 25°)[d] Present study[a]	Calcd Strain (gas, 25°)[d] Allinger[b]
Tricyclo[4.3.1.1^{3,8}]undecane (homoadamantane)[f]		−29.96	−27.77	−1.19	14.59	17.18
Tricyclo[4.4.1.1^{3,8}]dodecane (1,5-bishomoadamantane)[q]		−25.79	−23.82	−1.97	23.89	26.32
Tricyclo[4.4.1.1^{3,9}]dodecane (1,3-bishomoadamantane)[r]		−25.53	−22.64	−2.89	24.15	27.50
Tricyclo[5.3.1.1^{3,9}]dodecane (1,1-bishomoadamantane)[r]		−26.22	−22.36	−3.86	23.46	27.78
[2.2.2]Propellane[s]		41.90	42.74	−0.84	73.28	74.44
[3.3.3]Propellane		−30.28	−28.98	−1.38	16.49	18.29
[4.4.4]Propellane[t]		−47.93	−48.96	1.03	14.23	13.88
Tetracyclo[6.3.1.0^{2,6}.0^{5,10}]dodecane (ethanoadamantane)[m]		−25.52	−27.19	1.67	18.22	16.88
Tetracyclo[5.3.1.1^{2,6}.0^{4,9}]dodecane (iceane)[u]		−18.72	−21.51	2.79	25.02	22.56
Tetracyclo[6.4.0.0^{2,10}.0^{5,9}]dodecane		−4.30	−5.35	1.05	39.44	38.72
Pentacyclo[6.4.0.0^{2,6}.0^{4,12}.0^{7,11}]-dodecane[v]		6.69	7.42	−0.73	44.49	45.42
exo,endo-Tetracyclo[6.2.1.1^{3,6}.0^{2,7}]-dodecane[v]		−2.90	−2.70	−0.20	40.84	41.37
exo,exo-Tetracyclo[6.2.1.1^{3,6}.0^{2,7}]-dodecane[v]		−3.86	−3.26	−0.60	39.88	40.81
endo,endo-Tetracyclo[6.2.1.1^{3,6}.0^{2,7}]-dodecane[v]		6.15	6.32	−0.17	49.89	50.39
Tetracyclo[4.2.0.0^{2,5}.0^{3,8}]octane (dihydrocubane)		88.86	91.31	−2.45	111.98	114.62
Pentacyclo[4.3.0.0^{2,5}.0^{3,9}.0^{4,7}]-nonane (homocubane)[w]		95.72	99.31	−3.31	118.13	121.46
Pentacyclo[4.4.0.0^{2,5}.0^{3,10}.0^{4,7}]-decane (basketane)[x]		85.21	91.77	−6.56	112.75	119.39

Table XII (*Continued*)

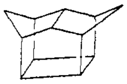
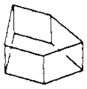
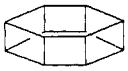
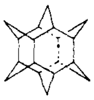
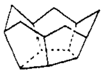
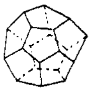
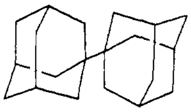
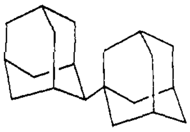
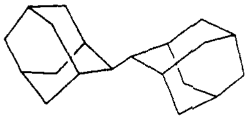
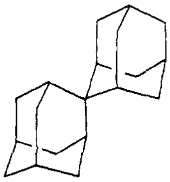
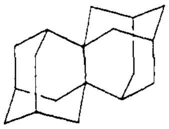
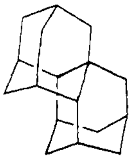
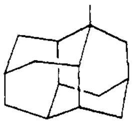
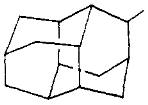
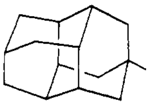
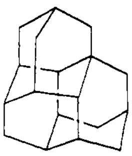
Alkane	Structure	Calcd $\Delta H_f°$ (gas, 25°)			Calcd Strain (gas, 25°)[d]	
		Present study[a]	Allinger[b]	Diff[c]	Present study[a]	Allinger[b]
Hexacyclo[5.4.1.$0^{2,6}$.$0^{3,10}$.$0^{5,9}$.$0^{8,11}$]-dodecane (birdcage hydrocarbon)[y]		25.67	31.64	−5.97	57.53	63.57
Hexacyclo[5.3.0.$0^{2,6}$.$0^{3,10}$.$0^{4,9}$.$0^{5,8}$]-decane (housane)		114.12	123.51	−9.39	135.72	145.06
Heptacyclo[6.4.0.$0^{2,7}$.$0^{3,12}$.$0^{4,11}$.-$0^{5,10}$.$0^{6,9}$]dodecane (hexaprismane)		129.27	144.73	−15.46	155.19	170.59
Heptacyclo[12.4.0.$0^{2,7}$.$0^{4,17}$.$0^{5,10}$.$0^{8,13}$.-$0^{11,16}$]octadecane (hexaasterane)[z]		58.70	57.77	0.93	115.40	114.77
Hexacyclo[7.5.1.$0^{3,13}$.$0^{5,12}$.$0^{7,11}$.-$0^{10,14}$]pentadecane (peristylane)[aa]		−8.64	14.61	−23.25	38.61	62.11
Dodecahedrane[bb]		−0.22	45.28	−45.50	42.98	88.38
1,1′-Biadamantane[o]		−53.66	−56.84	−3.18	21.46	18.93
1,2′-Biadamantane[o]		−50.97	−53.97	−3.00	23.04	20.64
2,2′-Biadamantane[o]		−53.20	−55.74	−3.54	19.70	17.71
[1]Diadamantane[cc]		−43.37	−46.52	3.15	25.51	22.90
[2]Diadamantane[dd]		−42.57	−45.05	2.48	22.29	20.34
[3]Diadamantane[ee]		−34.89	−36.39	1.50	23.73	22.65
1-Methyldiamantane[n]		−43.56	−44.43	0.87	12.69	12.06
3-Methyldiamantane[n]		−46.82	−47.21	0.39	9.43	9.28

Table XII (*Continued*)

		Calcd $\Delta H_f°$ (gas, 25°)			Calcd Strain (gas, 25°)[d]	
Alkane	Structure	Present study[a]	Allinger[b]	Diff[c]	Present study[a]	Allinger[b]
4-Methyldiamantane[n]		−42.91	−43.35	0.44	12.23	11.98
Triamantane[ff]		−44.36	−44.51	0.15	13.45	13.65

[a] Calculations based on force field in Table III. [b] Our calculations using force field described in ref 10a. [c] Difference between enthalpy calculations for the two force fields. [d] Strain energies evaluated using strain-free group increments in Table VI. [e] For energies of other conformations, see Table XIV. [f] Flexible polycycloalkanes, see ref 23a for discussion. [g] J. C. Coll, D. R. Crist, M. C. G. Bario, and N. J. Leonard, *J. Amer. Chem. Soc.*, 94, 7092 (1972); M. Doyle, W. Parker, P. A. Gunn, J. Martin, and D. D. MacNicol, *Tetrahedron Lett.*, 3619 (1970). [h] B. R. Vogt, S. R. Suter, and J. R. E. Hoover, *ibid.*, 1609 (1968). [i] A. Nickon, H. Kwasnik, T. Swartz, R. O. Williams, and J. B. DiGiorgio, *J. Amer. Chem. Soc.*, 87, 1613, 1615 (1965). [j] P. v. R. Schleyer and E Wiskott, *Tetrahedron Lett.*, 2845 (1967). [k] See ref 23e for discussion. [l] *Cf.* G. B. Clemans, M. N. Essiet, and R. L. Tyson, *J. Org. Chem.*, **37**, 2312 (1972). [m] S. Hala and S. Landa, *Angew. Chem.*, 78, 1060 (1966). [n] See ref 23c for discussion. [o] See ref 23d for discussion. [p] See ref 10a for discussion on the strain in this molecule. [q] F. N. Stepanov, M. I. Novikova, and A. G. Jurtschenko, *Synthesis*, 653 (1971). [r] T. Sasaki, S. Eguchi, and T. Takeshi, *J. Org. Chem.*, **36**, 3460 (1971). [s] P. E. Eaton and G. H. Temne, III, Abstracts, 165th Meeting of the American Chemical Society, Dallas, April 8, 1973, ORGN 58. [t] O. Ermer, R. Gerdil, and J. D. Dunitz, *Helv. Chim. Acta*, **54**, 2476 (1971). [u] Not yet prepared; *cf.* L. F. Fieser, *J. Chem. Educ.*, **42**, 408 (1965). [v] S. Winstein and R. L. Hansen, *Tetrahedron Lett.*, **25**, 4 (1960); H. D. Scharf, *Tetrahedron*, **23**, 3057 (1967) [w] C. G. Chin, H. W. Cuts, and S. Masamune, *Chem. Commun.*, 880 (1966). [x] S. Masamune, H. W. Cuts, and M. G. Hogben, *Tetrahedron Lett.*, 1017 (1966). [y] Heat of formation available for solid ($\Delta H_f°(c) = +12.06 \pm 0.27$ kcal/mol). Based on an arbitrary estimate for the heat of sublimation (12 kcal/mol), $\Delta H_f°(g) = +24$ kcal/mol has been proposed: C. T. Mortimer, "Reaction Heats and Bond Strengths," Pergamon Press, New York, N. Y., 1962, pp 45–46. [z] Not yet prepared; *cf.* H. Musso, *Umschau*, **68**, 209 (1968). [aa] P. E. Eaton and R. H. Mueller, *J. Amer. Chem. Soc.*, **94**, 1014 (1972). [bb] Not yet prepared; *cf* R. B. Woodward, T. Fukunaga, and R. C. Kelly, *ibid.*, **86**, 3162 (1964), and footnote *aa*. [cc] W. D. Graham and P. v. R. Schleyer, *Tetrahedron Lett.*, 1179 (1972); E. Boelema, J. Strating, and H. Wynberg, *ibid.*, 1175 (1972). [dd] W. D. Graham, P. v. R. Schleyer, E. Hagaman, and E. Wenkert, *J. Amer. Chem. Soc.*, **95**, 5785 (1973). [ee] Not yet prepared; *cf.* footnote *dd*. [ff] V. Z. Williams, Jr., P. v. R. Schleyer, G. J. Gleicher, and L. B. Rodewald, *J. Amer. Chem. Soc.*, **88**, 3862 (1966).

Table XIII. Calculated Strain Component Energies (kcal/mol)

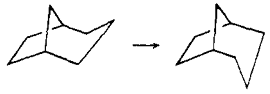
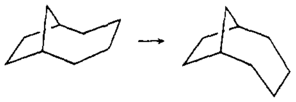
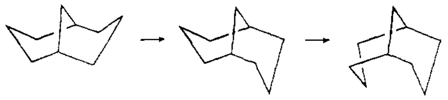
				Nonbonded interaction							
Alkane	Force field	Bond stretch energy	Angle bending energy	H···H	C···H	C···C	Total bonded energy	Bond torsion energy	Bend-stretch energy	Total[a] steric energy	Strain[b] energy 25°
Adamantane	Present study[c]	1.16	0.64	5.58	−0.79	6.78	11.57	0.02		18.77	12.95
	Allinger[d]	1.21	1.46	10.60	−4.38	−0.59	5.63	0.01	−0.24	13.11	11.23
Bicyclo[2.2.2]-octane	Present study[c]	0.92	0.70	5.27	−0.64	7.56	12.12	5.57		14.01	6.87
	Allinger[d]	1.20	1.99	10.06	−5.60	1.87	2.58	4.52	−0.23	5.02	5.94
Twistane	Present study[c]	2.15	4.18	6.12	0.10	14.18	20.40	6.52		33.26	26.12
	Allinger[d]	2.09	5.53	10.02	4.84	−0.38	−4.80	5.34	−0.79	16.97	17.89
1,1-Bishomo-adamantane	Present study[c]	1.64	9.90	13.34	−1.34	3.00	15.01	5.45		32.00	30.90
	Allinger[d]	3.75	8.45	24.14	−7.71	−3.02	13.41	4.29	−1.48	28.42	27.78
Cubane	Present study[c]	0.26	143.75	−0.25	−0.76	8.95	7.94	19.20		171.20	165.9
	Allinger[d]	5.18	133.88	−0.64	−2.80	−0.01	−3.44	30.00	−9.92	155.70	166.9
Dodecahedrane	Present study[c]	0.48	4.75	14.62	−5.08	−6.59	2.96	48.00		56.18	43.0
	Allinger[d]	2.00	5.57	30.70	−14.48	−7.23	8.98	45.00	−1.18	60.38	88.38

[a] Sum of strain components of eq 1. [b] Calculated enthalpy minus strain-free enthalpy based on group increments in Table VI. [c] Calculations based on force field described in Table III. [d] Our calculations based on force field described in ref 10a.

judged good, within 4 kcal/mol fair, and greater than 4 kcal/mol, poor. On this basis, out of the 84 compounds in Table XII, the heats of formation of 55 compounds are within 2 kcal/mol, 22 fall in the 2-4 kcal/mol range, and only 7 have deviations greater than 4 kcal/mol. While it appears that the two force field calculations generally agree quite well, there are disturbing exceptions. The 45.5 kcal/mol difference between calculated enthalpies for dodecahedrane is a glaring example!

Differences between two force fields in evaluating nonbonded interactions is the major factor underlying agreement or disagreement between calculated energies in Table XII. Each force field is composed of a different balance of the various nonbonded interactions (H···H, C···H, and C···C), and an understanding of how these components blend together enables an evaluation of the trends to be expected in the calculated results for each force field and also indicates where large deviations are to be anticipated. Analysis of the nonbonded component strains in Table XIII illustrates how differences between the nonbonded potential functions for the two force field influence the calculated enthalpies. Our force field has a more repulsive C···C nonbonded potential, while Allinger's model employs a harder H···H potential. Good agreement between the two

Table XIV. Conformational and Isomerization Enthalpies for Some Alkanes (kcal/mol)

Process[a]	Exptl	Calcd	
		Present study[b]	Allinger[c]
	Conformational Enthalpies		
Cyclohexane: twist boat → chair	5.5,[d] 5.9[e]	5.8	4.9
Cycloheptane: twist boat → twist chair		4.0	3.3
Cyclooctane:[f] crown → TCC → BC		−0.2, −0.1	1.8, 0.5
Cyclononane:[f] TCB → TCC → TBC		0.7, 0.0	1.1, 1.0
Cyclodecane:[f] crown → BCB → TCCC		13.8, 0.6	17.8, 1.7
Cycloundecane:[f] I → II		2.8	2.6
Bicyclo[3.2.1]octane: 		5.3	6.1
Bicyclo[4.2.1]nonane: 		1.8	0.3
Bicyclo[3.3.1]nonane: 		5.7, 2.5	4.3, 1.3
Methylcyclopentane: ax → eq		1.1	0.6
Methylcyclohexane: ax → eq	1.7–1.9[g]	1.8	1.6
tert-Butylcyclohexane: ax → eq	(∼5)[g,h]	5.4	6.6
	Isomerization Enthalpies		
2-Methylnorbornane: endo → exo	0.9[i]	0.8	0.8
Methyladamantane: 2-Me → 1-Me	3.4[j]	3.9	3.9
tert-Butyladamantane: 2-*t*-Bu → 1-*t*-Bu		2.8	2.9
Tricyclo[4.2.0.0^{2,5}]octane: syn → anti		4.9	4.2
Tricyclo[4.2.1.0^{2,5}]nonane: endo → exo		4.8	5.3
Tricyclo[4.2.1.1^{2,5}]decane: syn → anti		9.7	11.3
Tricyclo[5.2.1.0^{2,6}]decane: endo → exo	(∼3)[k]	4.5	4.8
Tricyclo[5.2.1.0^{1,5}]decane: endo → exo		7.4	6.3
Tetracyclo[6.2.1.1^{3,6}.0^{2,7}]dodecane: endo,endo → exo,endo → exo,exo		9.1, 1.0	9.0, 0.6
Bishomoadamantane: 1,1- → 1,3- → 1,5-		−0.7, 0.3	0.3, 1.2
Methyldiamantane: 3-Me → 1-Me → 4-Me	0.64, 2.14[l]	0.6, 3.3	1.1, 2.8
Biadamantane: 1,2′- → 1,1′- → 2,2′-	2.3, 1.11[m]	2.33, 0.46	1.58, 1.10

[a] Energy differences reported for structures connected by arrows. Positive energies indicate that the process is favored. See Table XII for absolute enthalpies and structures. [b] Calculations based on force field described in Table III. [c] Our calculations using force field described in ref 10a. [d] N. L. Allinger and L. A. Freiberg, *J. Amer. Chem. Soc.*, **82**, 2393 (1960). [e] W. S. Johnson, J. L. Margrave, and W. N. Hubbard, *ibid.*, **83**, 606 (1961). [f] See Table XV and text for description of conformations. [g] E. L. Eliel, N. L. Allinger, S. J. Angyal, and G. A. Morrison, "Conformational Analysis," Wiley, New York, N. Y., 1965. [h] Crude estimate. [i] Free-energy difference at 300°: R. J. Ouellette, J. D. Rawn, and S. N. Jreissaty, *J. Amer. Chem. Soc.*, **93**, 7117 (1971). [j] Reference 23c. [k] Free-energy difference: P. v. R. Schleyer and M. M. Donaldson, *J. Amer. Chem. Soc.* **82**, 4645 (1960). [l] D. E. Johnston, M. A. McKervey, and J. J. Rooney, *J. Chem. Soc., Chem. Commun.*, 1209 (1972). [m] Reference 23d.

force field calculations is realized when C···C and H···H interactions are of comparable importance, *e.g.*, adamantane or bicyclo[2.2.2]octane (Table XIII). However, if either of these strain components alone contribute in a significant way to the total steric energy of a molecule, then large discrepancies between the two force field calculations are expected. For example, twistane (Table XIII) has several short C···C nonbonded distances (∼2.57 Å) and our more repulsive C···C potential finds this molecule considerably more strained than Allinger's model. Alternately, in 1,1-bishomoadamantane many repulsive H···H interactions are present, and a higher strain is calculated with Allinger's force field than with ours.

Tri-*tert*-butylmethane, a molecule expected to have a large nonbonded strain component, is calculated by Allinger's force field to have only 1.9 kcal/mol total nonbonded strain compared with 20.8 and 17.5 kcal/mol evaluated with our force field and with Boyd's, respectively (Table XI). The large nonbonded contribution calculated for this molecule by our force field is compensated in Allinger's model by his more positive tertiary (CH) and quaternary (C) general group increments which increase the strain by about 17 kcal/mol (3 C + 1 CH, Table VI); reasonable agreement between the calculated enthalpies results. In effect, Allinger's approach includes strain in his general group increments. This is apparent in Table VI. Cubane illustrates a similar situation where the steric energy calculated by Allinger's force field is 16 kcal/mol (8 CH units) less than ours, but the calculated enthalpies agree within ∼1 kcal/mol (Table II). In this case, however, Allinger's more positive general group increments are compensating not so much for nonbonded strain differences but for the larger angle bending strain. When uncrowded structures lacking angle strain but possessing unusually large numbers of CH groups are compared. large deviations between the force field calculations are noted (six of the seven compounds with deviations over 4 kcal/mol in Table XII

Table XV. Calculated Conformations for Medium-Ring Cycloalkanes (C_8–C_{12})[a]

Cyclooctane	Crown	85.6, −82.1, 86.9, −90.7	−90.7, −87.0, −82.2, 85.8	
	TCC	60.7, −83.7, 111.7, −83.7	−83.6, 111.6, −83.7, 60.7	
	BC	−68.3, 100.3, −41.9, −65.0	68.1, −101.1, 43.4, 64.0	
Cyclononane	TCB	66.4, −70.6, −49.3, 101.3	66.0, −70.9, −48.8, 101.4	−86.3
	TBC	55.4, −123.1, 55.8, 55.7	55.9, −123.6, 55.9, 55.4	−123.0
	TCC	64.0, −117.3, 74.6, −85.2	64.1, −118.5, 74.9, −84.5	−117.5
Cyclodecane	TCCC	−67.7, 83.3, −144.3, 144.6, −83.3	83.4, −144.7, 144.3, −83.0, 67.7	
	Crown	−108.1, 107.8, −107.3, 107.7, −108.1	107.8, −107.7, 107.8, −107.6, 107.9	
Cycloundecane	I	−68.2, −81.6, 165.5, −90.4, 65.5	−127.5, −88.2, 78.0, −149.4, 159.0	−86.5
	II	−42.5, 145.0, −152.6, 55.8, 56.2	−43.5, 142.2, −152.0, 57.9, 57.5	−144.4
Cyclododecane		−66.4, −66.4, 148.3, −69.2, −69.8, 166.6	166.6, −70.0, −69.1, 148.3, −66.4, −66.5	

[a] Conformations described in terms of dihedral angles around carbon framework. Dihedral angles reported here are average of values calculated using force fields described in Table III and ref 10a. Notation for conformations followed nomenclature given in ref 5 (see text for discussion).

fall in this category). The extreme is provided by dodecahedrane where the steric energy owing to angle and nonbonded strains is only 0.4–0.7 kcal/mol per CH group compared with 16.4–18.8 kcal/mol per CH group in cubane.

Dodecahedrane provides a pregnant illustration of the inherent dangers and the care that must be taken in making predictions with an empirical method such as molecular mechanics. Considering the good agreement realized with the experimental data in Table II, it would have been difficult to anticipate such a large discrepancy (45.5 kcal/mol) between the results of the two force fields for dodecahedrane. Such large discrepancies will be expected to arise with structural types where insufficient experimental data are available to parameterize the force fields accurately.

While calculated absolute enthalpies may sometimes differ considerably from experimental values, agreement of relative energies of closely related systems is much better.[22a,f,g,23a,c] This results from a cancelation of some of the errors in the force fields. Representative conformational and isomerization energies, summarized in Table XIV, support this view. For example, the two force field calculations of the heats of formation for the three isomeric biadamantanes (Table XII) differ by 3–4 kcal/mol; however, when relative enthalpies of the three isomers are considered, the agreement between the two force fields is within ~0.6 kcal/mol (Table XIV).

In the medium-ring cycloalkanes where a number of conformations are possible, we have evaluated the most probable conformations based on experimental findings[30] and on previous molecular mechanics calculations.[5,6,9,10] The conformations examined are summarized in Table XV in terms of the dihedral angles described by the carbon framework of the ring. Where possible the notation developed by Hendrickson[5] in characterizing the different conformations has been followed.

The two force field models predict different preferred conformations for cyclooctane (Table XIV): Allinger's model finds the boat–chair conformation (BC) 0.5 and 1.8 kcal/mol more stable than the twist chair–chair (TCC) and crown conformations respectively; while our force field calculations indicate the three conformations to be very similar in energy. Experimentally, both the BC and crown conformations have been found in X-ray determinations on cyclooctyl derivatives; however, the majority of structures studied favor the former conformation.[30,33] Evidence from dynamic nmr analysis of deuterated[34] and fluorinated[35] cyclooctanes point toward the boat–chair as the major conformation; but the data do not completely rule out the possibility of a mixture of conformations including the crown conformation. In fact, the gas-phase electron diffraction data on cyclooctane were not compatible with the assumption of any single geometry, rather with a mixture of several conformations.[36] Earlier calculations[5,6,9] on the conformation of cyclooctane are in qualitative agreement with those in Table XIV, that is, a number of conformations close in energy. The larger energy difference calculated between the crown and BC conformers of cyclooctane by Bixon and Lifson (3.6 kcal/mol)[9b] and Hendrickson (2.8 kcal/mol)[5b] may be the result of symmetry constraints imposed on the ring[5b] or on the hydrogens[9b] during minimization which prevent complete relaxation of the molecular structure. Calculations by Wiberg[6] without

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(33) R. Srinivasan and T. Srikrishnan, *Tetrahedron*, 27, 1009 (1971).

(34) F. A. L. Anet and M. S. Jacques, *J. Amer. Chem. Soc.*, 88, 2585, 2586 (1966).

(35) J. E. Anderson, E. S. Glazer, D. L. Griffth, R. Knorr, and J. D. Roberts, *ibid.*, 91, 1386 (1969).

(36) A. Almenningen, O. Bastiansen, and H. Jensen, *Acta Chem. Scand.*, 20, 2689 (1966).

symmetry constraints gave an energy difference of only 0.2 kcal/mol favoring the BC over the crown conformation. It is our experience that minimization with symmetry constraints can lead to higher energies than those found when these artificial conditions are removed.

In cyclodecane, both force fields favor a twisted chair–chair–chair geometry (TCCC) over the boat–chair–boat conformation (BCB). The available X-ray data on several substituted derivatives find the BCB conformation for the ring (Table VIII).[30] However, in the solid state the conformational choice may be influenced by the lattice forces, and it is possible that one conformation may be favored in the crystal for a molecule for which a conformational mixture is found in the gas phase.[30] Earlier calculations by Hendrickson[5b] on cyclodecane indicated the BCB conformation to be 7.5 and 19.5 kcal/mol more stable than the CCC and crown geometries. However, these conformations were minimized with symmetry constraints; when these restrictions are removed, the CCC structure distorts to a twisted CCC conformation (TCCC) which is more stable than the BCB conformation! Equation 3 illustrates the changes in the dihedral angles during minimization starting from the symmetrical CCC conformation.

$$\underset{\text{CCC}}{\frac{-73.0,\ 115.0,\ -150.3,\ 115.0,\ -73.0}{73.0,\ -115.0,\ 150.3,\ -115.0,\ 73.0}} \longrightarrow \underset{\text{TCCC}}{\frac{-67.7,\ 83.3,\ -144.3,\ 144.6,\ -83.3}{83.4,\ -144.7,\ 144.3,\ -83.0,\ 67.7}} \tag{3}$$

Very little experimental information is available on the other medium rings (C_9, C_{11}, C_{12}). Three conformations for cyclononane were examined (Table XV) and were found to be close in energy. Again, the energy differences between the various conformers is less pronounced than previous calculations[5b] indicated owing to the removal of symmetry restrictions during minimization in our calculations. The TCB conformation correspond to that found experimentally for cyclononylamine hydrobromide.[30] Two conformations of cycloundecane were examined. Conformation I was calculated by both force fields to be 2.7–2.8 kcal/mol more stable than conformation II, the structure suggested by Bixon and Lifson.[9b] The calculated conformation for cyclododecane in Table XV corresponds to the one derived from an X-ray crystallographic study.[30]

Conclusion

The ability of molecular mechanics to accurately calculate the structures and enthalpies of large organic molecules has been examined through extensive calculations on a wide variety of structurally diverse alkanes using two force field models. Most molecular geometries are calculated with an accuracy rivaling the precision of the experimental methods (0.01 Å in bond lengths and 1–2° in angles). Further, the structures calculated do not appear to be a sensitive function of the choice of parameters for the force field within reasonable limits. Explicit inclusion of a 1,3 nonbonded interaction term seems to be required in order to more accurately reproduce the bond lengths in four-membered rings and small polycyclic molecules. Calculated bond angles at the ring junctions of fused four-membered rings exhibit large deviations (~5°) from experimental values. Redefining the preferred equilibrium structural parameters seems necessary for systems highly distorted from normal alkane values.

Heats of formation are somewhat less reliably evaluated than structures; however, confidence in the results is high for the majority of hydrocarbons, especially those lacking unusual structural features. Agreement between our force field calculation and that of Allinger's model is generally within 2 kcal/mol. Exceptions can be expected for systems displaying extreme structural features or possessing an excess of one type of unfavorable steric interaction. These areas of difficulty are identified by large discrepancies between the results of the two force field calculations. Compounds composed predominantly of quaternary or tertiary carbons (*e.g.*, dodecahedrane) display the largest disagreement between the force field calculations. These problems arise due to the lack of sufficient experimental data to parameterize these groups correctly. Relative energies are much more reliably determined than absolute enthalpy calculations since defects in the method tend to cancel.

The medium-ring cycloalkanes were found to have more low energy conformations than indicated by earlier molecular mechanics calculations.[5,6,9] Some of these studies imposed artificial symmetry constraints during minimization which led to higher energies. Middle-ring hydrocarbons can avoid the unfavorable nonbonded interactions in symmetrical structures by twisting.

Tables of fundamental data are beautiful! Basic principles of nature are revealed to the perceptive. But accurate experimental data are collected slowly, and chemical thought can easily outpace a gradual experimental accumulation. It is, after all, easier to ponder the relationships between meaningful numbers than to gather them. Given the problem of obtaining new enthalpy data on saturated hydrocarbons and considering the time, effort, and expense involved in carrying out the appropriate experimental measurements, molecular mechanics is clearly a preferable alternative. For example, the calculation of the structure and energy of a typical hydrocarbon of moderate size (~C_{10}) requires by our procedures 30–60 min of human effort, and $25–50 of computer time (2–5 min with an IBM 360-91). Furthermore, the accuracy realized at present by molecular mechanics calculations rivals in many cases that achieved by experimental methods. The calculations not only are able to lead the experimentalist to interesting problems but also provide a tool for the quantitative interpretation of experimental results.

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Supplementary Material Available. A listing of calculated Cartesian coordinates will appear following these pages in the microfilm edition of this volume of the journal. Photocopies of the supplementary material from this paper only or microfiche (105 × 148 mm, 20× reduction, negatives) containing all of the supplementary material for the papers in this issue may be obtained from the Journals Department, American Chemical Society, 1155 16th St., N.W., Washington, D. C. 20036. Remit check or money order for $3.00 for photocopy or $2.00 for microfiche, referring to code number JACS-73-8005.

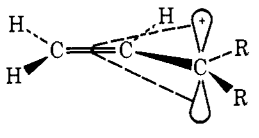
Substituent Effects on σ-π Conjugation. The Absence of π-Electron Transmission through Cyclopropane Rings[1,2]

R. S. Brown and T. G. Traylor*

Contribution from the Department of Chemistry, University of California, San Diego, La Jolla, California 92037. *Received March 3, 1973*

Abstract: Charge-transfer frequencies of acceptor complexes with 2-methoxy-1-phenylcyclopropane and similar compounds have been used to show that a 1,2-substituted cyclopropane does not transmit π-electron density from an electron-rich to an electron-deficient π center in the manner of a π bond. The rapid solvolysis of 2-methoxycyclopropylcarbinyl p-nitrobenzoate is interpreted as resulting from distortional stabilization in the form of fragmentation.

There is an enormous literature demonstrating that the strained cyclopropane ring acts as a simple π-electron donor in a manner similar to that of ethylene.[3–7]



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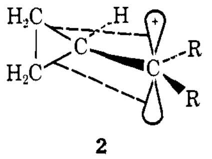

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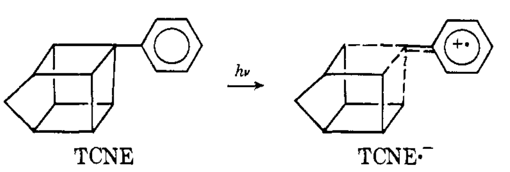
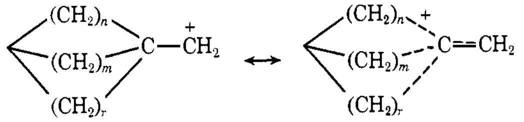
Recent evidence shows that other strained rings behave similarly, as illustrated below for the very strained homocubane group.[8a] The charge-transfer frequencies



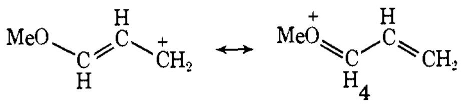
(1)

reveal a $\sigma^+_{p\text{-homocubyl}} = -0.75$ compared to $\sigma^+_{p\text{-cyclopropyl}} = -0.54$ and $\sigma^+_{p\text{-MeO}} = -0.78$. We can quite generally write σ-π conjugated forms of such strained, primary cations.



3

If this σ-π delocalization in 2 and 3 behaves like π-π delocalization in 1, then we might reasonably expect conjugation through the strained ring as in 5. This has been called π-σ-π conjugation[8b] or through-bond interaction[7b] (n, m, r = 0 to 2).



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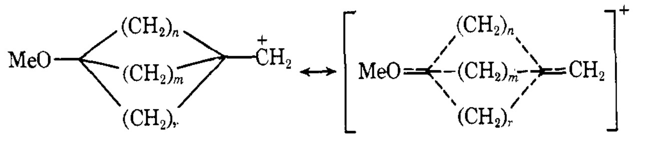
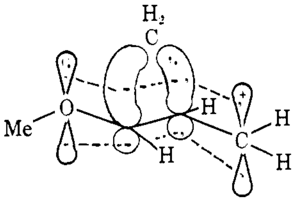


5

To apply this possible π-σ-π conjugation to cyclopropane we could fix an electron-acceptor π system (e.g., CH_2) to one position and an electron-donating π group (e.g., MeO) to another so as to maximize overlap of the proper Walsh orbitals to each group.



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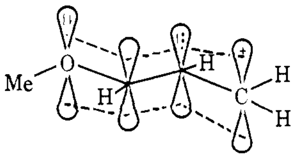

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(2) Presented at the Pacific Conference on Chemistry and Spectroscopy, Anaheim, Calif, October, 1971.

(3) P. v. R. Schleyer and V. Buss, *J. Amer. Chem. Soc.*, 91, 5880 (1969). This paper contains an extensive reference list covering both experimental and theoretical treatments of cyclopropylcarbinyl derivatives.

(4) J. C. Martin and B. R. Ree, *ibid.*, 91, 5882 (1969).

(5) W. J. Hehre, *ibid.*, **94**, 6592 (1972).

(6) D. S. Kabakoff and E. Namanworth, *ibid.*, 92, 3234 (1970).

(7) (a) R. Hoffmann and R. B. Davidson, *ibid.*, 93, 5700 (1971); (b) R. Hoffmann, E. Heilbronner, and R. Gleiter, *ibid.*, 92, 706 (1970).

(8) (a) N. A. Clinton, R. S. Brown, and T. G. Traylor, *ibid.*, 92, 5228 (1970); (b) T. G. Traylor, W. Hanstein, H. J. Berwin, N. A. Clinton, and R. S. Brown, *ibid.*, 93, 5715 (1971); (c) W. Hanstein, H. J. Berwin, and T. G. Traylor, *ibid.*, 92, 829 (1970); (d) T. G. Traylor, H. J. Berwin, J. Jerkunica, and M. L. Hall, *Pure Appl. Chem.*, 30, 599 (1972).