The Evaluation of Strain and Stabilization in Molecules Using Isodesmic Reactions

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Heats of Formation, $\Delta H_{\rm f}(g)$ (1-3)

We commonly discuss the stability of compounds relative to the standard states of the component elements (graphite, H₂, etc., at 25°C, 1 atm pressure), which are arbitrarily assigned heats of formation of 0.0 kcal/mole.

REFERENCE:
$$mC$$
, $n/2$ H₂ $\Delta H_f = 0$ O_2 $\Delta H'_{comb}$ $O_2 + H_2O$ $\Delta H_f = ?$ $O_2 + H_2O$ $O_3 + H_2O$ $O_4 + H_2O$ $O_4 + H_2O$ $O_5 + H_2O$ $O_6 + H_2O$ $O_7 + H_2O$ $O_8 + H_2$

Since the compound can seldom be formed directly from the elements, the heat of formation is often determined from heats of combustion: $\Delta H_{\rm f} = \Delta H'_{\rm comb} - \Delta H_{\rm comb}$. In combustion experiments the samples are usually liquids or solids. Since we are interested in *intra* molecular energies only, we must correct $\Delta H_{\rm comb}$ or $\Delta H_{\rm f}$ for the heat necessary to overcome intermolecular forces in the sample, which is the heat of vaporization (or sublimation): $\Delta H_{\rm f}({\rm g}) = \Delta H_{\rm f}(1) + \Delta H_{\rm v}$.

 $\Delta H_{\rm f}(g)$ becomes more exothermic (negative) in homologous series as the number of bonds increases: CH₄, -17.8 kcal/mole; C_2H_6 , -20.0; C_3H_8 , -25.0, etc., yet the larger molecules are not less reactive. A similar problem exists with cyclopropane $[\Delta H_f(g) = 12.7]$ relative to benzene $[\Delta H_f(g) = 19.8 \text{ kcal/mole}]$. The less endothermic value does not reflect greater stability. This seems to imply that we can compare only isomeric compounds, but, in fact, we can consider non-isomers if we choose some other reference state. One could use values of C—C and C-H bond dissociation energies, and examine deviations of the compounds from bond additivity, but there are no unique values for BDE's, even in unstrained compounds. The energies of hypothetical models can be calculated, but the results depend on the assumptions made and the method (a few experimental thermochemical data for benzene have been interpreted as demonstrating stabilization of <20 to >40 kcal/ mole).

Isodesmic Reactions

These reactions, introduced by Pople (4), "are examples of (hypothetical) chemical changes in which there is retention of the number of bonds of a given formal type (C—H, C—C, C—C) but with a change in their formal relation to one another." The following are examples. For the reaction, $\Delta H = \Sigma \Delta H_f(g)$ (Products) $-\Sigma \Delta H_f(g)$ (Reactants).

$$\begin{array}{c} \stackrel{H}{\longleftarrow} + 3 \text{ CH}_4 \xrightarrow{-19.5} 3 \text{ CH}_3 \text{CH}_3 \\ \\ & & \\ \end{array} + 6 \text{CH}_4 \xrightarrow{*39.3} 3 \text{ CH}_3 \text{CH}_3 + 3 \text{CH}_2 \text{=-CH}_2 \\ \end{array}$$

Numerous quantum and thermochemical errors cancel, so "the energies of isodesmic reactions measure deviations from the additivity of bond energies." The enthalpies of reaction (calculated from independently measured heats of formation)

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represent the strain in cyclopropane and the resonance stabilization of benzene. We can thus relate the energy of a molecule to the energies of a few simple reference molecules.

The choice of reference molecules is significant. Comparison of $\Delta H_{\rm f}(g)$ values for a series of methyl derivatives (CH₃X, X $-NO_{2}$, -OH, $-NH_{2}$, $-OCH_{3}$, -H, -CN, $-CO-CH_{3}$, and —COOH) with the corresponding ethyl derivatives shows differences of 2.3-7.9 kcal/mole, whereas the primary alkyl derivatives beginning with ethyl have quite uniform methylene increments (CH₃CH₂X versus CH₃CH₂CH₂CH₂X differences are 4.7–5.3 kcal/mole/CH₂) (2). Similarly, $\Delta H_{\rm f}(g)$ of tert-butyl and the isomeric 1-butyl derivatives differ by 1.9-10.9 kcal/mole. It is therefore desirable to include in isodesmic reactions reactants and products with alkyl groups of two carbon atoms or more, and to convert reactants with primary, secondary, or tertiary functional groups to products with the same structural features. Chlorocyclopropane and chloroethylene, for example, are secondary derivatives which should be converted into the simplest secondary chloroalkane, 2-chloropropane. (Note that C-1 of chloroethylene forms only one carbon-hydrogen bond, and two carbon-carbon bonds, and, in this sense, is a secondary carbon. Similarly, 1-chloro-1-methylcyclohexane, chlorobenzene, and chloroacetylene should give tert-butyl chloride as one of the products.)

Improved methods using these principles have been proposed by Bock (5) (homodesmotic reactions), and by Dill, Greenberg, and Liebman (6) (group separation reactions), and will be used in the following discussion. We will also illustrate a related method, metathetical isodesmic reactions.

Strain Energies of Cycloalkanes

Cyclopropane consists of three methylene groups $(-CH_2-)$ in a strained ring. In a hypothetical reaction with ethane the methylene groups will be transferred to propane:

$$\Delta H_{\rm f}({\rm g}) = 12.7 \pm 0.1 \; (3) \; \; 3(-20.1 \pm 0.05) \; \; \; \; 3(-25.0 \pm 0.1)$$

 $\Delta H({\rm reaction}) = 3(-25.0) - 12.7 - 3(-20.1) = -27.4 \; {\rm kcal/mole}$

Since the reaction is exothermic we are converting a strained reactant to an unstrained one. The strain energy is $-\Delta H(27.4\pm0.3~\text{kcal/mol})$. The "conventional ring strain energy" (CRSE) derived from bond energy additivity schemes (2) is 27.5 kcal/mole.

Other cycloalkanes can be involved in similar reactions:

Ring	ΔH (Group Separation)	CRSE		
	-27.4 ± 0.3 kcal/mole	27.5		
<i>с-</i> С ₃ Н ₆ <i>с-</i> С₄Н ₈	-26.4 ± 0.4	26.5		
C-C ₄ П8 C-C ₅ H ₁₀	-5.8 ± 0.5	6.2		
C-C ₆ H ₁₂	0.1 ± 0.5	0.0		
C-C ₇ H ₁₄	-6.0 ± 0.6	6.2		
C-C7014 C-C10H20	-12.1 ± 0.9	12.3		
C-C ₁₅ H ₃₀	-1.5 ± 1.2	1.8		
C-C ₁₆ H ₃₂	-1.5 ± 1.3	1.8		

In all cases $-\Delta H$ and the CRSE are in excellent agreement.

Alkenes

Energies of cycloalkenes or branched alkenes can be related to simple alkanes and alkenes (5), or to alkanes only (6). In the latter (group separation) method =CH2 or -CH2- of an alkene is changed to propane, -CH= becomes isobutane,

becomes neopentane. The number of hydrogen atoms attached to a carbon atom remains unchanged. Aromatic C—H groups are similarly converted to isobutane, and substituted aromatic carbon atoms (C-X) become tert-butyl-X, by reaction with ethane.

A traditional view of alkene stability is based on heats of hydrogenation (7, 8).

carbon atom of ethylene has two carbon-carbon bonds, and two C—H bonds). But even in the alkanes this would be a -7.1kcal/mole transformation. The unique stabilizing effects of a methyl group attached to ethylenic carbon (whether hyperconjugation or other factors) is not 7.7 - 5 = 2.7 kcal/mole, but rather, 7.7 - 7.1 = 0.6 kcal/mole, and this is the quantity that isodesmic reactions evaluate. The remaining 2.1 kcal/ mole of stabilizing effect is common to alkanes and other homologous series, and cannot result from a "special" electronic interaction of the methyl group and π electron system.

Aromatic Compounds

Resonance and hyperconjugative interactions of substituents with aromatic rings is an old concept of organic chemistry (9, 10) which is more readily demonstrated for charged and

There have been many years of discussion of how the methyl group of propylene stabilizes that compound by 2.7 kcal/mole relative to ethylene. Similarly, additional methyl groups attached to the ethylenic carbons lead to additional stabilization, although cis methyls also contribute some steric destablization. The most stable alkenes are those with the least exothermic heats of hydrogenation.

To gain insight into the problem, let us consider $\Delta H_f(g)$ for alkanes: propane (-25.0 kcal/mole), butane (-30.2), 2methylpropane (-32.1), pentane (-35.0), 2-methylbutane (-36.8), and 2,2-dimethylpropane (-40.0). If we insert a methylene group into a primary C-H bond of propane or butane, $\Delta H_f(g)$ of the resulting products (butane and pentane) are 5 kcal/mole more exothermic. In the insertion of CH_2 into the secondary C—H bond of propane, $\Delta H_{\rm f}({\rm g})$ of the product 2-methylpropane is 7.1 kcal/mole more exothermic. CH2 insertion into the tertiary C-H bond of 2-methylpropane produces 2,2-dimethylpropane, and $\Delta H_{\rm f}({
m g})$ becomes 7.9 kcal/mole more exothermic. This is equivalent to saying that branched alkanes have more highly exothermic values of $\Delta H_{\rm f}({
m g})$ than do the normal isomers, possibly because the former have a larger number of strong primary C—H

With alkenes each CH2 insertion into the primary (methyl) C—H bonds in the series propene → 1-butene → 1-pentene changes $\Delta H_f(g)$ by the usual -5 kcal/mole. But the change from ethylene to propylene is -7.7 kcal/mole. This, however, involves CH2 insertion into a secondary C-H bond (each radical intermediates than for the ground states of neutral molecules. However, the heats of hydrogenation of benzene derivatives (to the cyclohexanes) vary with the substituent. This has been taken of evidence of conjugation, although the effect of methyl substitution is somewhat less than in alkenes. The cyano group appears to have a destabilizing effect.

However, enthalpies of the isodesmic reactions are essentially identical, demonstrating that neither methyl, hydroxyl, phenyl, nor cyano substituents promotes significant net stabilization, although cancelling stabilizing and destabilizing effects may be occurring.

Metathetical Isodesmic Reactions

An alternative, and somewhat more accurate treatment of aromatic reactions involves a metathetical relationship (11). Since only two reacting molecules and two product molecules are involved, the uncertainties in ΔH (reaction) are relatively small compared to group separation reactions involving many molecules.

$$H + Me_3C - H' \xrightarrow{0.0} \longrightarrow H' + Me_3C - H$$

$$H + Me_3C - H \xrightarrow{0.0 \pm 0.2} \longrightarrow H + Me_3C - CH_3$$

$$CN + Me_3C - H \xrightarrow{0.0 \pm 0.6} \longrightarrow H + Me_3C - CN$$

$$OH + Me_3C - H \xrightarrow{0.3 \pm 0.7} \longrightarrow H + Me_3C - OH$$

$$-23 - 321$$

$$A compound which does show stabilization is$$

CH=CH, + Me₂C—H
$$\stackrel{2.2:0.3}{\longrightarrow}$$
 $\stackrel{}{\bigcirc}$ H + Me₂C—CH=CH₂
35.35 $\stackrel{}{\longrightarrow}$ -14.41 The reaction is unfavorable (endothermic) primarily because

of the stabilization of styrene.

The data demonstrate that no net stabilization occurs in cyclopropyl cyanide, 1,1-dimethylcyclopropane, or cyclopropylamine. Only in cyclopropylbenzene is there a substantial (3.0 kcal/mole) stabilizing effect.

Other Compounds

Isodesmic reactions are not a substitute for various semiempirical or ab initio methods of calculating molecular energies but may be used in conjunction with these methods (4, 6). Isodesmic reactions can, simply and conveniently, permit the estimation of strain and conjugation energies based on experimental (or calculated) heats of formation. The versatility can be further illustrated with examples of cyclic ethers, a highly branched hydrocarbon, bicyclic hydrocarbons, and acetylenes, and is limited only by the availability of thermochemical data for the compound of interest and appropriate reference compounds.

Conjugation in Cyclopropane Derivatives

The cycloheptatriene-norcaradiene equilibrium

$$R \Rightarrow R$$

favors the norcaradiene only when the groups R are π electron acceptor groups such as —CN or phenyl. In a 1970 article (12), Hoffmann noted the ability of cyclopropane to enter into π -type conjugation with neighboring π electron systems such as cyano, and this is believed to be involved in the stabilization of cyano-substituted norcaradienes. Others have supported the concept of cyclopropane conjugation. Dill, Greenberg, and Liebman (6) calculated (at the STO-3G level) the following stabilizations of cyclopropanes by substituents: CH₃, 2.4 kcal/mole; CN, 5.8; and NH₂, 2.9. With the help of some new thermochemical data we recently measured (13), we may examine isodesmic reaction enthalpies for some cyclopropane derivatives:

Conventional ring strain energies (CRSE) of the cyclic ethers (2) and the steric repulsion energy (SRE) of 2,2,4,4tetramethylpentane (2) are very well reproduced by $-\Delta H$ values of the isodesmic reactions, as are the CRSE values of spiropentane, bicyclo[3.1.0]hexane, bicyclo[1.1.0]-butane, bicyclo[4.2.0]octane, and cubane. Acetylenes are stabilized by 2 kcal/mole per alkyl group, a value much larger than that for alkenes, but much less than that implied by heats of hydrogenation.

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Recommended Format for the Periodic Table of the Elements

American Chemical Society Committee on Nomenclature

K. L. Loening, Chairman

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A change in the use of the letters A and B to designate subgroups of elements in the periodic table made by publishers of periodic charts of the elements late in the 1970's brought to a head a problem in the use of these letters that has been around a long time. Although acknowledged by an occasional publication, this problem went unrecognized by the great majority of chemists. However, many did become concerned when new periodic charts appeared using A and B differently than on earlier charts, even though this change was an attempt to conform with the recommendations given in the 1970 IUPAC (International Union of Pure and Applied Chemistry) "Nomenclature of Inorganic Chemistry." The difference was noted by the Nomenclature Committee of the ACS Division of Inorganic Chemistry early in 1979 and publicized in the Division's Fall Newsletter (October 1979) where comments and suggestions to solve the problem were requested.

On behalf of the Nomenclature Committee of the ACS Division of Inorganic Chemistry, W. C. Fernelius and W. H. Powell prepared a thorough review of the problem which was presented to the ACS Committee on Nomenclature at its meeting in November 1981. The ACS Committee on Nomenclature adopted the interim position that the letters A and B should no longer be used in any way to designate element subgroups in the periodic table, recommended publication of the report as soon as possible, and asked the Nomenclature Committee of the ACS Division of Inorganic Chemistry, under the chairmanship of T. D. Coyle (Inorganic Materials Division, National Bureau of Standards, Washington, DC, 20234), to develop an alternative method for designating subgroups of elements in the periodic table. The report, "Confusion in the Periodic Table of the Elements," was published in THIS JOURNAL, 59 [6], 504 (1982), and was presented by Fernelius at the Seventh Biennial Conference on Chemical Education, August 8-12, 1982, in Stillwater, Oklahoma. In each case, comments and suggestions to solve the problem were earnestly solicited.

In still another effort to publicize the problem as widely as possible, thereby generating as many comments and sugges-

tions for a solution as possible, the paper "The Periodic Table: Historical Road to Confusion" was presented in the symposium "The Periodic Table in Chemical Education" at the ACS National Meeting in Seattle, Washington, March 24, 1983. This symposium was co-sponsored by the ACS Divisions of Chemical Education, Chemical Information, and Inorganic Chemistry, and the ACS Committee on Nomenclature.

The comments and suggestions arising from all of the above efforts combined with opinions and suggestions from various committees and other groups produced a large number and variety of possible schemes for designating subgroups of elements in the periodic table. Fortunately, for the most part they could be grouped into just a few basic formats: those that were purely arbitrary; those distinguishing between main, representative, or characteristic elements and transition elements; and those reflecting electronic structure. Accordingly, four periodic table formats were considered thoroughly at a meeting of the Nomenclature Committee of the ACS Division of Inorganic Chemistry in Washington, D.C., on August 29, 1983; and the one shown below was selected for recommendation to the ACS Committee on Nomenclature as the official periodic table format of the American Chemical Society. The Nomenclature Committee of the ACS Division of Inorganic Chemistry was satisfied that this recommended format met all the minimum requirements for subgroup designations. It provides an unequivocal designation for each subgroup in the 18-column periodic table. In addition, it distinguishes the "d-block" elements and provides a means for identifying the "f-block" elements. There is a notational relationship with the Mendeleev subgroups, similar to the former "A" and "B" subgroups, e.g., former subgroups 3A and 3B are now 3d and 13; the same units digit is retained. Further, this recommended format is fully compatible with the current tentative position of the IUPAC Commission on Nomenclature of Inorganic Chemistry.

On November 14, 1983, the ACS Committee on Nomenclature concurred with the Nomenclature Committee of the ACS Division of Inorganic Chemistry by approving the periodic table format shown below.

Recommended Format for the Periodic Table of the Elements

											The Elements						
1	2	3d	4d	5d	6d	7d	8d	9d	10d	11d	12d	13	14	15	16	17	18
н																•••	
Li	Be																He
												В	С	N	0	F	Ne
Na	Mg												-		_	г	Ne
K	Ca	Sc										Αl	Si	P	S	CI	Ar
		SC	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	A -	0-		
Rb	Sr	Υ	Zr	Nb	Мо	T -						Ga	Ge	As	Se	Br	Kr
Cs	Ra	10.	1.16	140	MO	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te		Xe