

Does the Anomeric Effect in Ketals Depend on the Hybridization of the Central Carbon Atom?

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Enthalpies of formation $\Delta H_f^\circ(\text{g})$ of ketals prepared from cyclopropanone, cyclobutanone, cyclopentanone, cyclohexanone, and 7-norbornanone with methanol, ethylene glycol, and 2,2-dimethyl-1,3-propanediol, as well as of acetals/ketals of acyclic aldehydes and ketones, have been determined by measuring their heats of combustion and their heats of sublimation/vaporization. Group increments defining the strain-free energy level have been derived from the collected experimentally determined $\Delta H_f^\circ(\text{g})$ values of *unstrained* acetals and ketals, and the anomeric stabilizations of these groups (given in brackets) have been calculated from a comparison of their group increments with those of ethers: $\text{CH}_2[\text{2O}, \text{C}]$ -64.9 (-20.2), $\text{CH}[\text{2O}, \text{C}]$ -63.5 (-21.3), $\text{C}[\text{2O}, \text{2C}]$ -61.9 (-26.8), $\text{CH}[\text{2O}, \text{Ph}]$ -58.4 (-16.2), $\text{C}[\text{2O}, \text{Ph}, \text{C}]$ -56.3 (-21.2), $\text{C}[\text{2O}, \text{2Ph}]$ -67.1 (-32.0) kJ mol^{-1} . Enthalpies of formation $\Delta H_f^\circ(\text{g})$ of cyclic and spirobicyclic

ketals have also been determined experimentally and compared with values obtained from molecular mechanics calculations (MM3). The close agreement of the results shows that the anomeric interactions, which are already integrated in the MM3 force field, are not dissimilar in the small-ring cyclic and spirobicyclic ketals investigated in this study. The hybridization of the anomeric carbon atom apparently has no influence on the size of the anomeric effect detectable. The strain enthalpies of the cyclic and spirobicyclic ketals have therefore been calculated from their $\Delta H_f^\circ(\text{g})$ values using the group increment scheme. Analysis and interpretation of all geminal interactions known in acetals/ketals is possible by means of a recently developed additivity scheme, and a single value of -38.6 kJ mol^{-1} has been obtained for the structural increment representing the inherent geminal O-C-O interactions.

Introduction

The stabilizing geminal interaction of two alkoxy substituents bound to the same carbon atom is the best known example of an *anomeric effect*.^[1] This stabilization, which is present in acetals and ketals, is interpreted in terms of conjugation between the lone pair of one oxygen atom and the σ^* orbital of the other.^[1] For *stereoelectronic* reasons, certain conformations are anomERICALLY better stabilized than others,^[2] which is believed to be the reason why such conformations are often favoured in equilibrium mixtures, e.g. in carbohydrate chemistry.^{[1][2]} From conformational equilibrium studies, however, only relative stabilities of anomers can be obtained rather than absolute values, and furthermore, selective solvent polarity effects also have to be considered.^[1] Therefore, the information obtained concerning anomer stabilities is mainly qualitative and seldom quantitative.

In contrast, we recently determined the anomeric stabilization of acetals/ketals^{[3][4]} and *gem*-difluoroalkanes^[5] as a bulk effect from their enthalpies of formation $\Delta H_f^\circ(\text{g})$. Thermochemical group increments of the Benson type for

the *gem*-disubstituted carbon atoms were derived from these values.^{[3][4][5]} For this purpose, $\Delta H_f^\circ(\text{g})$ is divided into *strain-free* group increments for all atoms and groups of a compound. This means that for strained structures the strain enthalpy H_s , which is obtained by force field calculations on a reference compound, is subtracted from the experimental enthalpy of formation $\Delta H_f^\circ(\text{g})$. As a reference, a corresponding hydrocarbon is used, in which CH_2 is present in place of e.g. the oxygen atom in a ketal. It was shown earlier^[6] that strain energies in cycloalkanes and cyclic ethers are similar so that extension of this to cyclic ketals seems reasonable.

The more negative the increment of a carbon bound to two oxygen atoms, the larger the anomeric stabilization. Quantitative stabilization enthalpies are obtained by comparison of these increments with those of the corresponding C and CH groups of alkanes and ethers.^{[3][4][7]} The difference in the stabilizing effect caused by introduction of a first alkoxy group (as in ethers) and of a second one (as in acetals or ketals) gives a quantitative thermochemical measure of the anomeric effect. The anomeric effects obtained in this way for acetals and ketals have recently been reviewed and were rationalized by a new concept of geminal

[◇] For Part 15, see ref. [5].

pairwise interactions of all groups attached to the carbon atom concerned.^{[4b][5]} For the O–C–O interaction, a value of $-38.6 \text{ kJ mol}^{-1}$ was consistently obtained in all types or strain-free acetals and ketals. Using this procedure for ortho esters and ortho carbonates, deviations from additivity of the geminal interactions between oxygen atoms, i.e. anomeric effects, were observed.^[4b]

In the present work, we assess whether the anomeric stabilization, defined as outlined above, varies with the

hybridization of the central *gem*-disubstituted carbon atom as, for example, in ketals of small-ring ketones or spiro compounds.

In the context of our earlier work, it has become apparent that acetals and ketals are rather hygroscopic, and hence some older $\Delta H_f^\circ(\text{g})$ literature data^{[6b][14]} had to be corrected. Therefore, we report herein more $\Delta H_f^\circ(\text{g})$ values of simple acetals and ketals, which were obtained under strictest exclusion of moisture, as a further test of

Figure 1

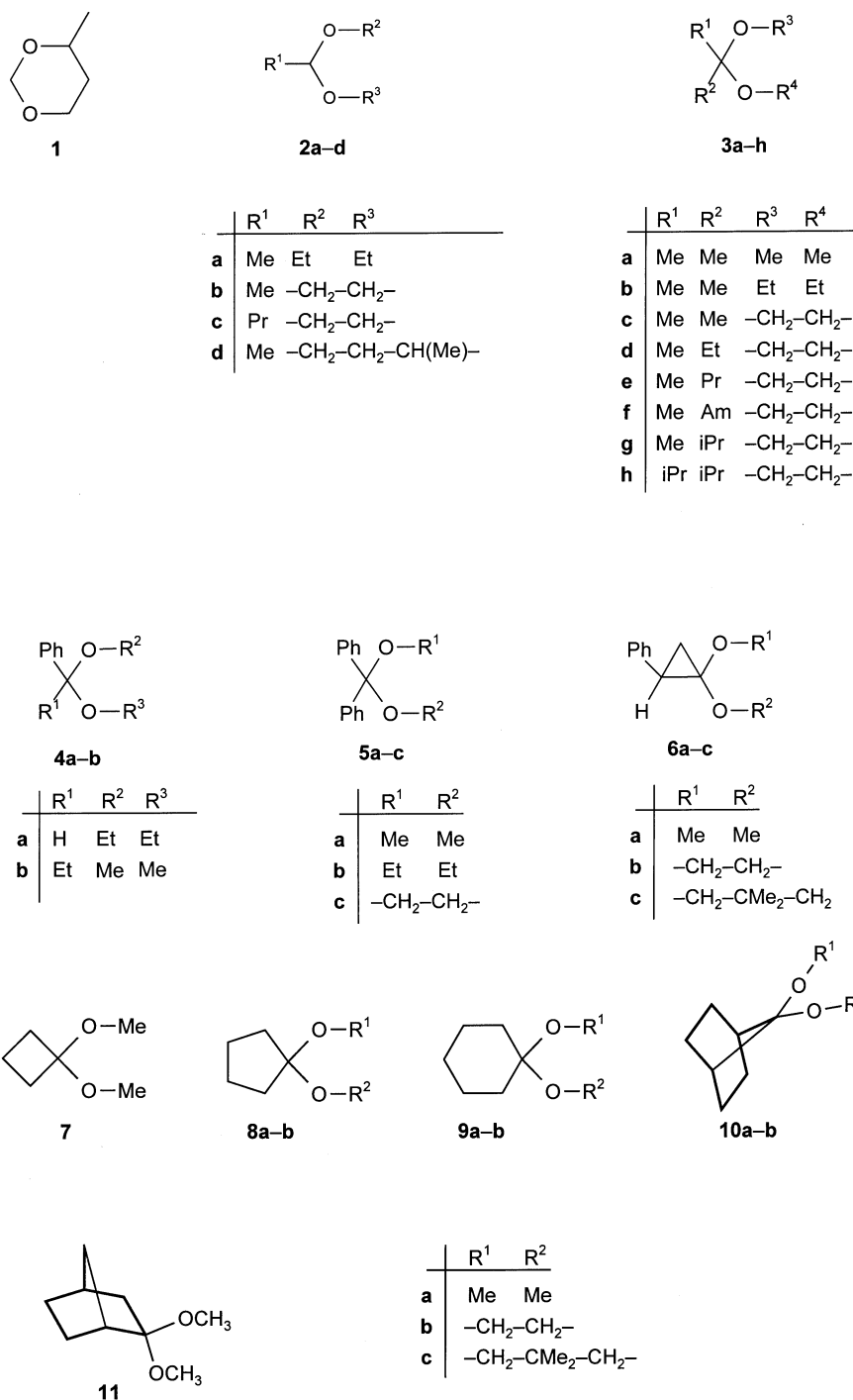


Table 1. Experimental thermochemical results^[a] for acetals and ketals

	State ^[b]	ΔH_c° (l or c) ^[c]	ΔH_f° (l or c)	$\Delta H_{\text{vap}}^\circ$ ^[d]	$\Delta H_{\text{sub}}^\circ$ ^[d]	ΔH_f° (g)
1	l	—	$-416.1 \pm 2.9^{[8]}$	43.74 ± 0.30	—	-372.4 ± 2.9
2a	l	-3868.79 ± 0.39	-493.07 ± 0.39	39.59 ± 0.33	—	-453.48 ± 0.51
2b	l	—	$-386.9 \pm 1.8^{[9]}$	43.13 ± 0.61	—	-343.8 ± 1.9
2c	l	-3644.06 ± 0.71	-431.98 ± 0.71	45.33 ± 0.34	—	-386.65 ± 0.79
2d	l	-3605.05 ± 0.54	-470.98 ± 0.54	45.06 ± 0.60	—	-425.92 ± 0.81
3a	l	—	$-460.95 \pm 0.9^{[10]}$	38.28 ± 0.42	—	-422.7 ± 1.0
3b	l	—	$-538.5 \pm 1.1^{[11]}$	43.87 ± 0.39	—	-494.6 ± 1.2
3c	l	-2966.21 ± 0.32	-430.49 ± 0.32	41.07 ± 0.16	—	-389.42 ± 0.36
3d	l	-3623.48 ± 0.42	-452.56 ± 0.42	43.13 ± 0.29	—	-409.43 ± 0.51
3e	l	-4280.0 ± 1.3	-475.4 ± 1.3	46.33 ± 0.34	—	-429.1 ± 1.3
3f	l	-5591.2 ± 1.1	-522.8 ± 1.1	54.03 ± 0.28	—	-468.8 ± 1.1
3g	l	-4289.6 ± 1.4	-465.8 ± 1.4	44.56 ± 0.24	—	-421.2 ± 1.4
3h	l	-5608.1 ± 1.3	-505.9 ± 1.3	49.93 ± 0.30	—	-456.0 ± 1.3
4a	l	-6242.4 ± 1.3	-372.8 ± 1.3	62.00 ± 0.59	—	-310.8 ± 1.4
4b	l	-6249.8 ± 1.5	-365.5 ± 1.5	57.93 ± 0.28	—	-307.6 ± 1.5
5a	c	-7918.7 ± 3.4	-270.6 ± 3.4	—	103.9 ± 1.6	-166.7 ± 3.8
5b	c	-9219.54 ± 0.81	-328.41 ± 0.84	—	97.1 ± 1.1	-231.3 ± 1.4
5c	c	-7695.3 ± 1.3	-208.0 ± 1.3	81.24 ± 0.64	99.7 ± 1.1	-108.3 ± 1.7
6a	l	-6099.7 ± 1.6	-229.7 ± 1.6	63.89 ± 0.60	—	-165.8 ± 1.7
6b	c	-5861.0 ± 1.1	-182.6 ± 1.1	69.62 ± 0.71	91.77 ± 0.81	-90.8 ± 1.4
6c	c	-7779.2 ± 1.2	-302.4 ± 1.2	—	97.50 ± 0.34	-204.9 ± 1.3
7	l	-3730.98 ± 0.90	-345.05 ± 0.90	42.30 ± 0.29	—	-302.75 ± 0.95
8a	l	-4309.7 ± 1.2	-445.7 ± 1.2	44.53 ± 0.35	—	-401.2 ± 1.3
8b	l	-4051.99 ± 0.91	-417.56 ± 0.91	47.59 ± 0.48	—	-370.0 ± 1.0
8c	l	-5990.2 ± 1.1	-517.4 ± 1.1	53.74 ± 0.51	—	-463.7 ± 1.2
9a	l	-4929.6 ± 1.2	-505.5 ± 1.2	49.02 ± 0.21	—	-456.5 ± 1.2
9b	l	-4682.0 ± 1.4	-466.9 ± 1.4	50.63 ± 0.56	—	-416.3 ± 1.5
9c	l	-6625.6 ± 3.0	-561.3 ± 3.0	58.99 ± 0.63	—	-502.3 ± 3.1
10a	l	-5404.4 ± 1.2	-423.8 ± 1.2	50.16 ± 0.22	—	-373.6 ± 1.2
10b	l	-5147.3 ± 1.0	-395.1 ± 1.0	53.80 ± 0.40	—	-341.3 ± 1.1
10c	c	-7064.3 ± 1.4	-516.1 ± 1.4	—	83.99 ± 0.87	-432.1 ± 1.7

^[a] Enthalpies in kJ mol⁻¹; reference temperature 298.15 K. — ^[b] Physical state of the samples to which the values of ΔH_c° and ΔH_f° apply; c = crystalline solid; l = liquid; g = gas. — ^[c] Calculated from the specific energies of combustion in Table 8. — ^[d] From the vapor pressures (Table 9) using the Clausius-Clapeyron equation.

the reliability of the reported method for assessing anomeric stabilization and as a possible basis for the re-evaluation of literature data. Furthermore, we have performed enthalpy of vaporization ($\Delta H_{\text{vap}}^\circ$) measurements for some acetals (**1**, **2b**, **3a**, and **3b**) with known ΔH_f° (l) values, so as to provide a broad base of ΔH_f° (g) data of ketals of acyclic ketones.

Results and Discussion

The Anomeric Effect in Regular Ketals

The acetals and ketals **1–10** investigated thermochemically in this context are depicted in Figure 1.

Besides the aliphatic standard systems **1–3**, we also studied acetals and ketals of α -phenyl-substituted aldehydes and ketones (**4** and **5**), as well as small-ring cyclic and bicyclic ketals **6–10**. The compounds were either prepared by standard syntheses as described in the Experimental Section, or were commercially available. All liquid samples were purified by repeated fractional distillation in a spinning-band column. The solids were purified by several crystallizations from pure, dry solvents. The purities of the samples were determined by GC to be > 99.9%, except in the case of **9a**, for which a correction had to be applied. The liquid samples were stored over molecular sieves and

the absence of water (< 0.05%) was checked by Karl-Fischer titration.

The enthalpies of combustion ΔH_c° of the acetals and ketals **1–10** were determined by combustion calorimetry in an isoperibolic macrocalorimeter with a stirred water bath. The details and the results for each compound are recorded in the Experimental Section. For **1**^[8], **2b**^[9], **3a**^[10], and **3b**^[11], the results of previous work were satisfactorily reproducible. The enthalpies of vaporization and sublimation were determined by the method of transference of a substance in a saturated N₂ stream at constant temperature, which we have described in detail recently^[4b]. Enthalpies of fusion were obtained by DSC.

The mean values of ΔH_c° for the condensed state, and of $\Delta H_{\text{vap}}^\circ$, $\Delta H_{\text{sub}}^\circ$, and ΔH_f° for the condensed and gaseous states of the compounds **1–10** are collected in Table 1. The standard deviation of the mean value for each series is given. The propagation of the error is calculated as the square root of the sum of the weighted variances.

For a re-evaluation of the best strain-free increments of acetals and ketals in the literature, we dissected the enthalpies of formation ΔH_f° (g) of **2–5** into strain-free increments. The strain enthalpies H_s (alkane) were calculated by MM3^{[12][13]} force field calculations on corresponding hydrocarbon structures in which the O of the acetal or ketal was replaced by CH₂. The data are presented in Table 2.

Table 2. Calculation of strain-free increments of acetals and ketals^[a]

compound	ΔH_f° (g)	H_s (alkane) ^[b]	increment ^[c]
dimethoxymethane	$-348.20 \pm 0.79^{[14]}$	0.0	CH₂[2O]
diethoxymethane	$-414.80 \pm 0.80^{[14]}$	0.0	–65.6
1,3-dioxolane	$-303.2 \pm 1.4^{[d]}$	26.0	–66.1
1,3-dioxane	$-349.86 \pm 0.89^{[e]}$	0.0	–64.6
4,4,6,6-tetramethyl-1,3-dioxane	$-470.6 \pm 3.3^{[15]}$	16.8	–63.9
			–63.0
1,1-dimethoxyethane	$-389.70 \pm 0.80^{[14]}$	0.0	CH[2O, C]
2a	-453.48 ± 0.51	0.0	–65.1
2b	-343.8 ± 1.9	26.0	–62.8
2c	-386.65 ± 0.79	26.0	–63.2
2d	-425.92 ± 0.81	0.0	–63.1
2,4,4,6,6-pentamethyl-1,3-dioxane	$-512.8 \pm 3.7^{[15]}$	16.8	–63.3
			–63.1
3a	-422.7 ± 1.0	0.0	C[2O, 2C]
3b	-494.6 ± 1.2	0.0	–56.0
3c	-389.42 ± 0.36	26.0	–61.8
3d	-409.43 ± 0.51	26.0	–66.7
3e	-429.1 ± 1.3	26.0	–65.4
3f	-468.8 ± 1.1	26.0	–63.5
3g	-421.2 ± 1.4	34.1	–60.3
3h	-456.0 ± 1.3	58.0	–61.6
2,2,4,4,6-pentamethyl-1,3-dioxane	$-520.9 \pm 3.8^{[15]}$	8.4	–63.1
			–55.3
4a	-310.8 ± 1.4	0.0	CH[2O, Ph]
dimethoxy(phenyl)methane	$-248.94 \pm 0.88^{[4a]}$	0.0	–54.2
2-phenyl-1,3-dioxolane	$-205.3 \pm 1.3^{[4a]}$	26.0	–58.5
5,5-dimethyl-2-phenyl-1,3-dioxolane	$-311.3 \pm 1.2^{[4a]}$	8.4	–58.8
			–61.9
4b	-307.6 ± 1.5	0.0	C[2O, Ph, C]
1,1-dimethoxy-1-phenylethane	$-288.5 \pm 1.5^{[4a]}$	0.0	–53.7
2,5,5-trimethyl-2-phenyl-1,3-dioxane	$-350.68 \pm 0.86^{[4a]}$	8.4	–56.0
			–59.2
5a	-166.7 ± 3.8	0.0	C[2O, Ph, C]
5b	-231.3 ± 1.4	0.0	–68.4
5c	-108.3 ± 1.7	12.0	–66.9
			–66.0

^[a] All values in kJ mol^{–1}; for mean values, see Table 3. – ^[b] Estimated strain enthalpies taken from a corresponding alkane (CH₂ in place of O). – ^[c] Thermochemical increment of the *gem*-disubstituted C in acetal/ketal. – ^[d] $\Delta H_f^\circ(l) = -337.2 \pm 1.4^{[9]}$, $\Delta H_{vap}^\circ = 34.02^{[17]}$. – ^[e] $\Delta H_f^\circ(l) = -388.94 \pm 0.88^{[18]}$, $\Delta H_{vap}^\circ = 39.08 \pm 0.04^{[19]}$.

The increments for the central carbon atoms of the acetals and ketals **2–5** were calculated as described previously^[4b]; the values are listed in Table 2 for all of the compounds, while the mean values are collected in Table 3 together with the corresponding increments for hydrocarbons and ethers.

It is satisfying to note that the standard increments in Table 3, which are based on a larger number of compounds than previously, do not deviate significantly from the earlier values.^[4] Thus, they can be considered as being reliable, and should be usable for the calculation of heats of formation of regular acetals and ketals.^[21] The anomeric effects, i.e.

the excess enthalpies caused by the geminal interactions $\Delta\Delta H_{gem}$ in acetals and ketals calculated from these increments as described previously^[4b], are listed in Table 4.

$$\Delta\Delta H_{gem} = \Delta H_{dioxo} - \Delta H_{alkyl} - 2(\Delta H_{oxy} - \Delta H_{alkyl})$$

This influence of the number of alkyl groups in the α -position on the anomeric effect has been explained in terms of a new concept of additive *structural increments* derived from the quantitative analysis of the group increments of hydrocarbons, ethers, acetals and ketals.^[4b] The pairwise geminal interactions between the atoms attached to the central carbon atom, i.e. H–C–C, H–C–O, C–C–O,

Table 3. Strain-free group increments for calculation of enthalpies of formation ΔH_f° (g) of ethers, acetals and ketals^[a]

$\Delta H_{alkyl}^{[16]}$		$\Delta H_{oxy}^{[4b]}$		$\Delta H_{dioxo}(\text{aliphatic})$		$\Delta H_{dioxo}(\text{aromatic})^{[b]}$	
CH ₃ [C]	–42.05	CH ₃ [O]	–42.05	–	–	–	–
CH ₂ [2C]	–21.46	CH ₂ [O, C]	–33.06	CH ₂ [2O]	–64.9	–	–
CH[3C]	–9.04	CH[O, 2C]	–25.64	CH[2O, C]	–63.5	CH[2O, Ph]	–58.4
C[4C]	–1.26	C[O, 3C]	–18.16	C[2O, 2C]	–61.9	C[2O, Ph, C]	–56.3
		O[2C]	–99.23			C[2O, 2Ph]	–67.1

^[a] All values in kJ mol^{–1}; neighbouring atoms in square brackets. – ^[b] Increment for the phenyl ring, Ph[C] = 92.13 kJ mol^{–1}.^[20]

Table 4. Stabilization of primary, secondary and tertiary groups by O in ethers ($\Delta\Delta H_{\text{oxy}}$) and in acetals and ketals ($\Delta\Delta H_{\text{gem}}$)^[a]

groups ^[a]	$\Delta\Delta H_{\text{oxy}}$ ^[c]	aliphatic ^[e]	$\Delta\Delta H_{\text{gem}}$ monophenyl ^[f]	diphenyl ^[g]
CH ₃ [O]	0.0	—	—	—
CH ₂ [O] _x , C ₂ — _x ^[d]	−11.6	−20.2	—	—
CH[O] _x , C ₃ — _x ^[d]	−16.4	−21.3	−16.2	—
C[O] _x , C ₄ — _x ^[d]	−16.9	−26.8	−21.2	−32.0

^[a] Calculated from the group increments (Table 3) [kJ mol^{−1}]. — ^[b] Groups of ethers ($x = 1$) and acetals and ketals ($x = 2$). — ^[c] $\Delta\Delta H_{\text{oxy}} = \Delta H_{\text{oxy}} - \Delta H_{\text{alkyl}}$. — ^[d] $\Delta\Delta H_{\text{gem}} = \Delta H_{\text{dioxy}} - \Delta H_{\text{alkyl}} - 2(\Delta\Delta H_{\text{oxy}})$. — ^[e] Alkyl groups attached. — ^[f] Ketals of alkyl phenyl ketones. — ^[g] Ketals of benzophenone.

O—C—O, as defined in this analysis, contribute to the differences between primary, secondary, and tertiary groups. The value of the geminal interaction term O—C—O (−38.6 kJ mol^{−1}), derived from multilinear regression analysis in application of this new additivity principle,^[4b] can be taken as a measure of the *inherent* interaction solely between the geminal oxygen atoms. Thus, it may be called the *inherent* anomeric stabilization and, as a result, is closely similar for all aliphatic acetals and ketals.^[4b]

The introduction of one phenyl ring at the α -position results in a decrease of the anomeric effect in acetals to −16.2 kJ mol^{−1} and in ketals to −21.2 kJ mol^{−1}. On the other hand, benzophenone ketals show a particularly high anomeric stabilization of −32.0 kJ mol^{−1}.

Steric and Anomeric Effects in Small-Ring Cyclic Ketals

The experimental enthalpies of formation $\Delta H_f^\circ(\text{g})$ of the cyclic and spirobicyclic ketals derived from cyclopropanone (**6a–c**), cyclobutanone (**7**), cyclopentanone (**8a–c**), cyclohexanone (**9a–c**), and 7-norbornanone (**10a–c**) are collected in Table 5, and the known value^[22] of the 2,2-dimethoxynorbornane **11d** is included for the sake of comparison. These data are compared with the enthalpies of formation of regular ketals. The strain-free reference values ΔH_f° (strain-free) for each compound (Table 5) are calculated as the sums of the appropriate group increments from Table 3. The difference is taken as the individual excess enthalpy of each compound and is called strain enthalpy H_s . This comprises all inherent steric and electronic stabilizing and destabilizing interactions present in the cyclic structures, including any *alteration* of the anomeric interaction. What could alter the anomeric interaction in small cyclic and bicyclic ketals in comparison to open-chain ketals? It is mainly the difference in hybridization of the central anomeric carbon that could change the overlap between the π and the σ^* orbitals of the two oxygen atoms, since the stereoelectronic requirements of this interaction are probably not violated.

The dominant contribution to the large values of H_s for the 3- and 4-membered-ring compounds (**6–7**) and for the norbornanone derivatives (**10a–c** and **11**) is the inherent ring strain of the carbon skeleton. The additional strain in

Table 5. Experimental enthalpies of formation, strain enthalpies of cyclic and spirobicyclic ketals, and comparison with calculated by MM3 values^[a]

com- pound	$\Delta H_f^\circ(\text{g})$	ΔH_f° ^[b] (strain-free)	H_s ^[c]	ΔH_f° (MM3) ^[d]	$\Delta\Delta H^\circ$ ^[e]
6a	−165.8 ± 1.7	−282.8	117.0	−[f][g]	(11.2) ^[k]
6b	−90.8 ± 1.4	−264.9	174.1	−[f][h]	(−15.6) ^[k]
6c	−204.9 ± 1.3	−350.2	145.3	−[f][i]	(1.6) ^[k]
7	−302.75 ± 0.95	−408.8	106.1	−309.0	−6.3
8a	−401.2 ± 1.3	−430.3	29.1	−399.0	2.2
8b	−370.0 ± 1.0	−412.3	42.3	−367.4	2.6
8c	−463.7 ± 1.2	−497.7	34.0	−463.6	0.1
9a	−456.5 ± 1.2	−451.8	−4.7	−443.8	12.7
9b	−416.3 ± 1.5	−433.8	17.5	−412.2	4.1
9c	−502.3 ± 3.1	−519.1	16.8	−509.1	−6.8
10a	−373.6 ± 1.2	−448.4	74.8	−374.9	1.3
10b	−341.3 ± 1.1	−430.4	89.1	−334.4	6.9
10c	−432.1 ± 1.7	−515.8	83.7	−440.1	8.0
11 ^[j]	−378.2 ± 3.8 ^[19]	−448.4	70.2	−373.5	4.7

^[a] All values in kJ mol^{−1}. — ^[b] Sum of strain-free group increments from Table 3. — ^[c] Strain enthalpies as difference $\Delta H_f^\circ(\text{g}) - \Delta H_f^\circ$ (strain-free) for ketals. — ^[d] Calculated by MM3^{[12][13]}, the enthalpy of the most stable conformer of each ketal is given. — ^[e] $\Delta\Delta H = \Delta H_f^\circ(\text{MM3})^{[13]} - \Delta H_f^\circ(\text{g})$, mean (e.s.d.) = 6.1 kJ mol^{−1}. — ^[f] Ketals of cyclopropanones cannot be calculated by MM3 because of missing structural and heat parameters.^[k] — ^[g] $H_s(\text{alkane}) = 141.3$ kJ mol^{−1}. — ^[h] $H_s(\text{alkane}) = 170.2$ kJ mol^{−1}. — ^[i] $H_s(\text{alkane}) = 151.6$ kJ mol^{−1}. — ^[j] 2,2-dimethoxynorbornane. — ^[k] Missing structural parameters have been estimated^[12] and a relative value for ΔH_f° has been calculated by MM3 ($\Delta\Delta H$ values from these estimated enthalpy data are given in parentheses).

the cyclic ketals, i.e. in the 1,3-dioxolanes **8b, c** and 5,5-dimethyl-1,3-dioxanes **9b, c**, is roughly similar to that in the ketals of acyclic ketones (see Table 2). However, the specific influence of the spiro connectivity in the cyclopropyl compounds **6b** and **6c** increases their strain by a considerable amount, $H_s(\text{6b}) = 174.1$ kJ mol^{−1}, compared to the monocyclic compound **6a** ($H_s = 117$ kJ mol^{−1}). This is most likely a steric effect, because the strain of the hydrocarbon analogue of **6b** (CH₂ in place of O) is very similar, $H_s(\text{alkane}) = 170.2$ kJ mol^{−1}.

In contrast, only a moderate increase of strain is caused by the spiro connection in the spirobicyclic ketals of 7-norbornanone **10b** and **10c**, as well as in the spirobicyclic ketals of cyclopentanone **8b** and **8c**, and of cyclohexanone **9b** and **9c**. The steric demand of the anomeric carbon at the 7-position of the bicyclo[2.2.1] skeleton is seemingly very similar to that of the anomeric carbons in five- and six-membered rings. The strain enthalpies of 7,7-dimethoxynorbornane (**10a**) and 2,2-dimethoxynorbornane (**11**) are very similar ($\Delta\Delta H_f^\circ = 4.7 \pm 3.8$ kJ mol^{−1}), in contrast to the related ketones, which show a large difference in strain enthalpy $H_s(7\text{-norbornanone}) - H_s(2\text{-norbornanone}) = 41$ kJ mol^{−1}.^[14]

A rigorous analysis and quantitative estimation of the full interplay of steric effects including the stereoelectronic part of the anomeric interaction has been performed by molecular mechanics calculations. We have calculated the enthalpies of formation of the ketals **7–11** by MM3 (Table 5). All ketals adopt a gauche conformation at both anomeric C—O bonds. As expected, the torsion angles O—C—O—C of the spiro ketals are lower than 60° as a

Table 6. Purities, temperatures of fusion T_{fus} , enthalpies of fusion ΔH_{fus} , densities d (293K), specific heat capacities c_p (298 K), and expansion coefficients for analysis of the combustion experiments

	purity (%)	$T_{\text{fus}}^{[a]}$ K	$\Delta H_{\text{fus}}^{[a]}$	$d(293\text{K})^{[b]}$ [g cm ⁻³]	$c_p(298\text{K})^{[a]}$ [J K ⁻¹ g ⁻¹]	$(\delta V/\delta T) 10^{-6}^{[c]}$ [l g ⁻¹ K ⁻¹]
2a	99.91	—	—	0.83	1.67	1.0
2c	99.99	—	—	0.94	1.08	1.0
2d	99.89	—	—	0.93	1.88	1.0
3c	99.99	—	—	0.93	1.89	1.0
3d	99.99	—	—	0.93	2.26	1.0
3e	99.99	—	—	0.96	1.46	1.0
3f	99.99	—	—	0.90	1.77	1.0
3g	99.99	—	—	0.93	1.86	1.0
3h	99.99	—	—	0.93	1.46	1.0
4a	99.99	—	—	0.96	2.15	1.0
4b	99.99	—	—	0.96	1.97	1.0
5a	99.97	380.0	27.8	1.22	1.30	0.1
5b	99.95	323.2	19.9	1.15	1.61	0.1
5c	99.99	328.1	15.9	1.18	1.21	0.1
6a	99.97	—	—	0.98	2.97	1.0
6b	99.99	303.1	22.6	1.20	1.58	0.1
6c	99.99	351.2	27.2	1.15	1.30	0.1
7	99.99	—	—	0.93	1.85	1.0
8a	99.99	—	—	0.94	2.18	1.0
8b	99.99	—	—	1.03	1.95	1.0
8c	99.97	—	—	0.98	1.47	1.0
9a	99.39 ^[d]	—	—	0.95	2.01	1.0
9b	99.99	—	—	1.03	1.92	1.0
9c	99.96	—	—	0.98	1.94	1.0
10a	99.99	—	—	1.01	1.98	1.0
10b	99.99	—	—	1.03	1.67	1.0
10c	99.99	346.7	23.9	1.13	1.30	0.1
polyethylene ^[e]	—	—	—	0.92	2.53	0.1
oil ^[f]	—	—	—	0.88	0.84	1.0
cotton ^[g]	—	—	—	1.50	1.67	0.1
Mylar ^[h]	—	—	—	1.38	1.32	0.1

[a] From DSC measurements, uncertainty in ΔH_{fus} of ± 0.2 kJ mol⁻¹. — [b] Measured with pycnometer. — [c] Estimated. — [d] Impurity (0.61%) cyclohexanone detected by GC. — [e] CH_{1.930}, $\Delta u_c^\circ(\text{polyethylene}) = -46361.0 \pm 3.1$ J g⁻¹. — [f] CH_{1.940}, $\Delta u_c^\circ(\text{oil}) = -45966.7 \pm 7.2$ J g⁻¹. — [g] CH_{1.774}O_{0.887}, $\Delta u_c^\circ(\text{cotton}) = -16945.2 \pm 4.2$ J g⁻¹. — [h] C₁₀H₈O₄, $\Delta u_c^\circ(\text{Mylar}) = -22838.8 \pm 4.8$ J g⁻¹, $m(\text{Mylar}) = m_{\text{Mylar, moist}} [1 - 4.64 \cdot 10^{-5} \text{ (relative moisture of air in \%)}]$.

function of the size of the ketal ring: $\omega_{(\text{O}-\text{C}-\text{O}-\text{C})} \approx 30^\circ$ in the 1,3-dioxolanes and $\approx 10^\circ$ in the 1,3-dioxanes. The right-hand column of Table 5 gives the difference between the calculated and experimental enthalpies of formation $\Delta\Delta H = \Delta H_f^\circ(\text{MM3}) - \Delta H_f^\circ(\text{g})$. These differences are small (e.s.d. = 6.1 kJ mol⁻¹) and random, with the exception of that for **9a**, the purity of which in the thermochemical work was less than satisfactory. Furthermore, the enthalpies of formation of the regular acyclic ketals in Table 2 are predicted by MM3 with the same degree of precision. Hence, the computational procedure used in MM3 predicts the same amount of anomeric stabilization as derived from our experimentally determined values of group increments. Accordingly, no alteration of the anomeric effect by differences in hybridization of the central *gem*-disubstituted C atom was found. The strength of the *inherent* anomeric interaction (38.6 kJ mol⁻¹) that we derived previously^[4a] based on acetals and ketals, must be similar in the ketals of cyclic and bicyclic ketones studied here.

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Experimental Section

The *General Methods* used in this study have been described in detail in previous reports^[5].

The compounds **1a**, **2a**, **3a–d**, **8b**, **9b** (Aldrich), **2b** (Avocado Research Chemicals), **2c–d**, **3e–h**, and **4a** (Hüls AG) were commercially available. All liquid samples were purified by repeated fractional distillations in a spinning-band column and were stored over molecular sieves. The absence of water (< 0.05%) was checked by Karl-Fischer titration. Solid compounds were purified by repeated recrystallizations from dry solvents. The purities of the samples were determined by GC ($\geq 99.9\%$) and are listed in Table 6.

The other ketals were prepared from the ketones and the appropriate alcohols under conditions of acid catalysis following literature procedures, and were characterized by their physical constants and NMR spectra. Purifications were carried out as mentioned above.

1,1-Dimethoxy-1-phenylpropane (**4b**)^[23]: B.p. 82–83°C/27 Torr (ref. [23] 92–93°C/18 Torr). — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 7.54, 7.48 (m, 2 H, Ph), 7.30, 7.18 (m, 3 H, Ph), 3.09 (s, 6 H, OCH₃), 1.96, 1.87 (quint, 2 H, CH₂), 0.64, 0.55 (t, 3 H, CH₂CH₃).

Dimethoxydiphenylmethane (**5a**)^[24]: M.p. 106.9°C (ref. [24] 107–108°C). — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 7.52, 7.58 (m, 4 H, Ph), 7.30, 7.20 (m, 6 H, Ph), 3.15 (t, 6 H, CH₃).

Table 7a. Results from typical combustion experiments of **2** and **3**^[a]

	2a	2c	2d	3c	3d	3e	3f	3g	3h
$m(\text{substance})$ [g] ^[b]	0.293768	0.338452	0.354335	0.346602	0.343260	0.322940	0.354777	0.357413	0.367465
$m'(\text{cotton})$ [g] ^[b]	0.001052	0.000979	0.001026	0.000969	0.000949	0.001209	0.000923	0.000975	0.000844
$m''(\text{polyethylene})$ [g] ^[b]	0.271763	0.469929	0.270287	0.267693	0.275302	0.476651	0.536105	0.448028	0.560646
ΔT_c [K] ^[c]	0.88521	1.29144	0.93731	0.89563	0.93510	1.30391	1.49000	1.29689	1.55477
$\varepsilon_{\text{calor}}(-\Delta T_c)$ [J] ^[d]	−22215.7	−32401.5	−23523.2	−22477.3	−23467.8	−32714.5	−37383.3	−32538.3	−39008.4
$\varepsilon_{\text{cont}}(-\Delta T_c)$ [J] ^[c]	−12.25	−18.40	−13.13	−12.51	−13.22	−18.76	−21.88	−18.78	−22.77
ΔE_{corr} [J] ^[c]	7.08	12.03	8.45	8.21	8.37	11.98	13.92	11.99	14.70
$-m'\Delta u'_c$ [J]	17.82	16.58	17.38	16.41	16.07	20.48	15.63	16.52	14.29
$-m''\Delta u''_c$ [J]	12599.2	21786.3	12530.8	12410.5	12763.3	22098.0	24854.4	20771.0	25992.1
$\Delta u_c(\text{substance})$ [J g ^{−1}]	−32686.9	−31329.4	−30982.9	−29005.1	−31147.9	−32827.5	−35289.2	−32892.1	−35401.0

^[a] All symbols are as used in ref. ^[36] $T_h = 298$ K; $V_{\text{bomb}} = 0.2664$ l; $p_{\text{gas}} = 30.45$ bar; $m_{\text{water}}^i = 0.78$ g; $E_{\text{ignition}} = 1.5$ J; $m_{\text{platinum}} = 12.18$ g. — ^[b] Corrected masses obtained from weight by calculating the buoyancy. — ^[c] $\Delta T_c = T^i - T^f + \Delta T_{\text{corr}}$; $\varepsilon_{\text{cont}}(-\Delta T_c) = e_{\text{cont}}^f(T^i - 298 \text{ K}) + e_{\text{cont}}^i(298 \text{ K} - T^f + \Delta T_{\text{corr}})$, ΔE_{corr} is sum of items 81–85, 87–90, 93, and 94 in ref. ^[36]. — ^[d] $\varepsilon_{\text{calor}} = 25096.64 \pm 0.51$ J K^{−1} (0.0022%) for **2a**, **2d**, **3c**, **3d**, and $\varepsilon_{\text{calor}} = 25089.0 \pm 1.2$ J K^{−1} (0.0048%) for **2c**, **3f**, **3g**, **3h** from calibration with benzoic acid.

Table 7b. Results from typical combustion experiments of **4**, **5**, **6**, and **7**^[a]

	4a	4b	5a	5b	5c	6a	6b	6c	7
$m(\text{substance})$ [g] ^[b]	0.353708	0.340232	0.367619	0.272542	0.364142	0.368789	0.383064	0.363857	0.384618
$m'(\text{cotton})$ [g] ^[b]	0.000862	0.001043	0.000752	0.001017	0.000840	0.000775	0.000845	0.000818	0.001057
$m''(\text{polyethylene})$ [g] ^[b]	0.619198	0.522888	—	0.099568 ^[e]	—	0.551591	—	—	0.485977
$m'''(\text{oil})$ [g] ^[b]	—	—	0.029429	—	—	—	—	—	—
ΔT_c [K] ^[c]	1.63209	1.43618	0.53501	0.57349	0.49356	1.52128	0.50771	0.51651	1.38941
$\varepsilon_{\text{calor}}(-\Delta T_c)$ [J] ^[d]	−40948.4	−36033.1	−13422.9	−14388.6	−12390.6	−38190.8	−12745.7	−12966.8	−34880.3
$\varepsilon_{\text{cont}}(-\Delta T_c)$ [J] ^[c]	−24.58	−21.13	−7.20	−7.51	−6.44	−23.15	−6.69	−6.76	−20.58
ΔE_{corr} [J] ^[c]	16.92	14.50	7.57	6.16	7.11	16.15	6.95	6.21	13.16
$-m'\Delta u'_c$ [J]	14.60	17.67	12.76	17.23	14.23	13.12	14.31	13.85	17.91
$-m''\Delta u''_c$ [J]	28706.6	24241.6	—	4580.5	—	25572.3	—	—	22530.4
$-m''' \Delta u'''_c$ [J]	—	—	672.12	—	—	—	—	—	—
$\Delta u_c(\text{substance})$ [J g ^{−1}]	−34585.9	−34620.4	−34645.2	−35923.8	−33981.9	−34195.5	−33231.2	−35596.6	−32078.5

^[a], ^[b], and ^[c] see Table 7a. — ^[d] $\varepsilon_{\text{calor}} = 25089.5 \pm 1.2$ J K^{−1} (0.0048%) for **4a**, **4b**, **5b**, $\varepsilon_{\text{calor}} = 25088.9 \pm 2.6$ J K^{−1} (0.0102%) for **5a** and $\varepsilon_{\text{calor}} = 25104.5 \pm 3.1$ J K^{−1} (0.0125%) for **5c**, **6**, **7** from calibration with benzoic acid. — ^[e] Combustion in mylar bags.

Diethoxydiphenylmethane (**5b**)^[25]: M.p. 50.1°C (ref.^[25] 51–51.5°C). — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 7.52, 7.58 (m, 4 H, Ph), 7.30, 7.20 (m, 6 H, Ph), 3.32 (quint, 4 H, CH₂), 1.23 (t, 6 H, CH₃).

2,2-Diphenyl-1,3-dioxolane (**5c**)^[26]: M.p. 55.1°C (ref.^[26] m.p. 55–56°C, b.p. 168°C/10 Torr). — IR (KBr): $\tilde{\nu}$ = 3035 cm^{−1}, 2955, 2865, 1600, 1310, 1210, 1075, 1020, 990, 945, 913, 780, 750, 700, 640. — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 7.11 (m, 5 H, Ph), 3.55 (s, 4 H, OCH₂).

1,1-Dimethoxy-2-phenylcyclopropane (**6a**)^{[27][28]}: B.p. 91°C/5 Torr (ref.^[28] 95°C/9 Torr). — IR (film): $\tilde{\nu}$ = 2910 cm^{−1}, 2805, 1270, 1210, 1150, 1030, 690. — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 7.17 (m, 5 H, Ph), 3.42, 3.25 (s, 6 H, CH₃O), 2.32 (q, 1 H, CH), 1.24, 1.18 (q, 2 H, CH₂).

1-Phenyl-4,7-dioxaspiro[2,4]heptane (**6b**)^[28]: B.p. 115°C/5 Torr (ref.^[28] 80–81°C/1 Torr). — IR (film): $\tilde{\nu}$ = 2900 cm^{−1}, 1175, 1050, 700. — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 7.15 (m, 5 H, Ph), 3.42, 3.25 (m, 4 H, CH₂O), 2.23 (q, 1 H, CH), 1.47 (9.2 H, CH₂).

6,6-Dimethyl-1-phenyl-4,8-dioxaspiro[2,5]octane (**6c**)^[28]: M.p. 78°C. — IR (KBr): $\tilde{\nu}$ = 2930 cm^{−1}, 2840, 1345, 1275, 1165, 1040, 1030, 685. — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 7.20 (m, 5 H, Ph), 3.40, 3.10, 3.02 (s, q, 4 H, CH₂O), 2.28 (q, 1 H, CH), 1.45, 1.35 (q, 2 H, CH₂), 1.00 (s, 3 H, CH₃), 0.40 (s, 3 H, CH₃). — C₁₄H₁₈O₂ (218.29): calcd. C 77.03, H 8.31; found C 77.14, H 8.21.

Cyclobutanone Dimethyl Ketal (**7**)^{[29][30]}: B.p. 63–64°C. — IR (film): $\tilde{\nu}$ = 2970 cm^{−1}, 2930, 2885, 2810, 1448, 1430, 1410, 1150,

1130, 1100, 1030. — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 3.01 (s, 6 H, OCH₃), 2.10 (t, 4 H, CH₂), 1.56 (m, 2 H, CH₂).

Cyclopentanone Dimethyl Ketal (**8a**)^{[29][30]}: B.p. 51°C/24 Torr. — IR (film): $\tilde{\nu}$ = 2930 cm^{−1}, 2840, 1440, 1423, 1180, 1130, 1105, 1040, 960. — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 3.09 (s, 6 H, CH₃), 1.74 (m, 4 H, C_αH₂), 1.54 (m, 4 H, C_βH₂).

8,8-Dimethyl-6,10-dioxaspiro[4,5]decane (**8c**)^{[29][30]}: B.p. 89°C/13.5 Torr (b.p.^[31] 135–137°C/30 Torr). — IR (film): $\tilde{\nu}$ = 2930 cm^{−1}, 2845, 1460, 1425, 1325, 1180, 1105, 960. — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 3.33 (s, 4 H, CH₂O), 1.91 (t, 4 H, C_αH₂), 1.57 (m, 4 H, C_βH₂), 0.80 (s, 6 H, CH₃).

Cyclohexanone Dimethyl Ketal (**9a**)^[29]: B.p. 71.5°C/24 Torr (ref.^[24] 63–65°C/22.5 Torr). — IR (film): $\tilde{\nu}$ = 3005 cm^{−1}, 2930, 2840, 2810, 1455, 1440, 1172, 1150, 1098, 1050, 916, 900. — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 3.05 (s, 6 H, CH₃), 1.64 (t, 4 H, C_αH₂), 1.443 (m, 4 H, C_βH₂), 1.25 (quint, 2 H, C_γH₂).

3,3-Dimethyl-1,5-dioxaspiro[5.5]undecane (**9c**)^{[29][30]}: B.p. 50°C/3 Torr (ref.^[31] 146–149°C/25 Torr). — IR (film): $\tilde{\nu}$ = 2915 cm^{−1}, 2840, 1455, 1435, 1260, 1150, 1100, 945, 900. — ¹H NMR (250 MHz, C₆D₆, TMS): δ = 3.32 (s, 4 H, CH₂O), 1.77 (t, 4 H, C_αH₂), 1.52 (quint, 4 H, C_βH₂), 1.29 (m, 2 H, C_γH₂), 0.78 (d, 6 H, CH₃).

Bicyclo[2.2.1]heptan-7-one Dimethyl Ketal (**10a**)^[32]: B.p. 66°C/15 Torr (ref.^[32] 80°C/30 Torr). — IR (film): $\tilde{\nu}$ = 2940 cm^{−1}, 2890, 2850, 2810, 1440–1460, 1323, 1172, 1135, 1090, 1050, 995. — ¹³C NMR (250 MHz, C₆D₆, TMS): δ = 50.5 (CH₃O), 96.7 (OCO), 37.8 (CH), 28.2 (CH₂).

Table 7c. Results from typical combustion experiments of **8**, **9**, and **10**^[a]

	8a	8b	8c	9a	9b	9c	10a	10b	10c
<i>m</i> (substance) [g] ^[b]	0.338181	0.376032	0.294407	0.350433 ^[e]	0.381504	0.327576	0.329515	0.335999	0.342131
<i>m'</i> (cotton) [g] ^[b]	0.000992	0.000823	0.001010	0.000930	0.000965	0.000929	0.000902	0.000987	0.000738
<i>m''</i> (polyethylene) [g] ^[b]	0.485173	0.564476	0.491815	0.587953	0.521087	0.574453	0.666266	0.578517	—
<i>m'''</i> (cyclohexanone) [g] —	—	—	—	0.0022	—	—	—	—	—
ΔT_c [K] ^[c]	1.34171	1.51574	1.32071	1.56561	1.46249	1.52965	1.68425	1.51500	0.49026
$\epsilon_{\text{calor}}(-\Delta T_c)$ [J] ^[d]	—33682.8	—38051.9	—33155.6	—39303.9	—36715.0	—38401.1	—42282.1	—38033.3	—12307.7
$\epsilon_{\text{cont}}(-\Delta T_c)$ [J] ^[c]	—19.65	—22.53	—18.98	—23.35	—24.65	—22.78	—25.33	—22.33	—6.41
ΔE_{corr} [J] ^[c]	12.42	15.34	12.25	14.97	14.53	14.67	16.74	15.30	4.94
$-m'\Delta u'_c$ [J]	16.80	13.94	17.11	15.75	16.35	15.74	15.28	16.72	12.51
$-m''\Delta u''_c$ [J]	22493.1	26169.7	22801.0	27258.1	24158.1	26632.2	30888.8	26820.6	—
$-m'''\Delta u'''_c$ [J]	—	—	—	77.4	—	—	—	—	—
Δu_c (substance) [J g ^{−1}]	−33055.3	−31577.3	−35130.7	−34128.1	−32894.2	−35899.5	−34551.4	−33338.0	−35937.1

^[a], ^[b], and ^[c], see Table 7a. — ^[d] $\epsilon_{\text{calor}} = 25104.5 \pm 3.1 \text{ J K}^{-1}$ (0.0125%). — ^[e] The impurity of 0.61 % cyclohexanone has been subtracted.

Table 8a. Specific energies of combustion ($-\Delta u_c^\circ$) as the results of all combustion experiments of **2–5** [J g^{−1}]

2a	2c	2d	3c	3d	3e	3f	3g	3h	4a	4b	5a	5b	5c
32686.9	31339.6	30988.3	29005.1	31147.9	32858.9	35289.2	32892.1	35363.1	34585.9	34615.5	34618.8	35933.4	33956.7
32691.4	31310.2	30982.9	29013.0	31140.3	32827.5	35269.8	32923.6	35370.4	34603.5	34647.7	34645.2	35923.8	33981.9
32682.3	31329.4	30994.8	29001.2	31160.9	32819.1	35260.8	32869.2	35401.0	34599.6	34651.7	34684.5	35926.4	33989.4
32678.3	31314.9	31002.7	29010.4	31154.4	32842.6	35298.9	32869.2	35398.3	34598.4	34620.4	34679.9	35921.7	33992.5
	31339.4		28999.4	31150.5	32823.7	35295.4	32909.3	35393.1	34567.4	34622.9	34614.2		34004.3
	31334.3				32792.8	35275.2					34695.0		33979.5
						35258.9							33979.1
													33974.5
													33989.6
													33985.4
													33970.7
mean value:													
32684.7	31328.0	30992.2	29005.8	31150.8	32827.4	35278.3	32892.7	35385.2	34591.0	34631.6	34656.3	35926.3	33982.1

Table 8b. Specific energies of combustion ($-\Delta u_c^\circ$) as the results of all combustion experiments of **6–10** [J g^{−1}]

6a	6b	6c	7	8a	8b	8c	9a	9b	9c	10a	10b	10c
34195.5	33220.6	35591.5	32078.5	33039.8	31557.2	35142.9	34117.3	32909.5	35899.5	34551.4	33342.7	35916.9
34214.6	33243.9	35596.6	32054.8	33055.3	31568.9	35141.2	34114.4	32864.6	35922.1	34532.7	33317.8	35950.5
34179.6	33231.2	35591.6	32091.9	33034.2	31577.3	35130.7	34152.2	32870.7	35874.7	34560.3	33338.0	35944.3
34172.1	33231.1	35600.5	32085.3	33088.5	31591.2	35125.3	34128.1	32894.2	35944.3	34526.9	33346.9	35937.1
34179.0		35576.6	32070.8	33063.2	31579.7	35123.3	34139.5	32870.1	35860.4	34557.2	33345.1	35941.8
		35601.8		33054.2								
		35602.5										
		35607.6										
mean value:												
34188.2	33231.7	35596.1	32076.3	33055.9	31574.9	35132.7	34130.7	32881.8	35900.2	34545.7	33338.1	35938.1

Bicyclo[2.2.1]heptan-7-one Ethylene Ketal (10b)^[33]: B.p. 80 °C/15 Torr. — IR (film): $\tilde{\nu} = 2940 \text{ cm}^{-1}$, 2855, 1460, 1440, 1332, 1195, 1082, 1040, 1010. — ¹H NMR (250 MHz, CCl₄/CD₃COCD₃, TMS): $\delta = 3.02$ (s, 4 H, CH₂O), 1.01 (m, 4 H, CH₂-*exo*), 0.78 (m, 2 H, CH), 0.35 (m, CH₂-*endo*).

Bicyclo[2.2.1]heptan-7-one 2,2-Dimethylpropylene Ketal (10c)^[33]: M.p. 73.5 °C (from cyclohexane). — IR (KBr): $\tilde{\nu} = 2960$ –2840, 1470, 1460, 1440, 1335, 1210, 1175, 1100, 1050, 1000, 980, 904, 790, 750. — ¹H NMR (250 MHz, CCl₄/CD₃COCD₃, TMS): $\delta = 2.58$ (s, 4 H, CH₂O), 1.27 (quint, 4 H, CH), 0.94 (quint, 4 H, CH₂-*exo*), 0.36 (quint, 4 H, CH₂-*endo*), 0.15 (s, 6 H, CH₃). — C₁₂H₂₀O₂ (196.29): calcd. C 73.47, H 10.27; found C 73.33, H 10.15.

Combustion Calorimetry – Enthalpies of Formation: The enthalpies of combustion of **2–10** were measured in an isoperibolic

macrocalorimeter^[34] surrounded by a stirred water bath with controlled temperature ($\pm 10^{-3} \text{ K}$).^[35] The energy equivalent of the calorimeter was calibrated using samples of benzoic acid (NIST, SRM 39i) to a precision of $\leq 0.01\%$. The detailed experimental procedures have been described previously^[35] and the reduction of the data to standard states was performed according to conventional procedures^[36] (see Table 6 for all auxiliary quantities used).

Crystalline compounds were pressed into tablets of 13 mm diameter and liquid samples were sealed into polyethylene ampoules (pipettes, NeoLab, Heidelberg) or into mylar bags. The purities of all compounds were checked by GC analysis and those of the solid compounds by analysis of the melting peak (DSC),^[37] see Table 6. The contribution of the cyclohexanone present in **9a** was calculated

Table 9. Results from measurements of the vapor pressure^[a]

	$p(298)$ [mbar]	$T^{[b]}$ [K]	$n^{[c]}$	$a^{[d]}$	$b^{[d]}$
1	22.3	273–313	9	20.75 ± 0.14	5.261 ± 0.036
2a	40.8	275–308	8	19.68 ± 0.17	4.762 ± 0.040
2b	97.0	270–308	9	21.97 ± 0.31	5.187 ± 0.074
2c	12.4	278–313	8	20.80 ± 0.16	5.452 ± 0.041
2d	21.8	273–313	9	21.26 ± 0.28	5.420 ± 0.072
3a	19.5	272–301	9	18.41 ± 0.20	4.604 ± 0.051
3b	28.3	273–308	9	21.04 ± 0.19	5.276 ± 0.047
3c	68.4	278–318	9	20.79 ± 0.08	4.940 ± 0.019
3d	22.4	274–313	9	20.51 ± 0.14	5.187 ± 0.035
3e	8.59	278–313	9	20.84 ± 0.15	5.572 ± 0.041
3f	0.932	278–318	9	21.73 ± 0.11	6.499 ± 0.034
3g	5.64	273–303	7	19.70 ± 0.11	5.358 ± 0.029
3h	2.15	278–318	9	20.91 ± 0.13	6.005 ± 0.036
4a	0.148	283–328	9	23.10 ± 0.22	7.457 ± 0.071
4b	0.254	288–328	9	22.00 ± 0.11	6.988 ± 0.034
5a	$3.89 \cdot 10^{-4[e]}$	302–352	9	34.07 ± 0.52	12.50 ± 0.19
5b	$1.61 \cdot 10^{-4}$	275–321	12	30.44 ± 0.34	11.68 ± 0.13
5c	$6.05 \cdot 10^{-5}$	276–319	9	30.50 ± 0.33	11.99 ± 0.13
5c	—	331–370	9	24.74 ± 0.20	9.771 ± 0.077
6a	$7.74 \cdot 10^{-2}$	278–313	16	23.21 ± 0.22	7.684 ± 0.072
6b	$1.30 \cdot 10^{-2}$	288–302	5	23.74 ± 0.24	8.374 ± 0.085
6b	—	307–333	6	23.68 ± 0.21	11.04 ± 0.10
6c	$1.18 \cdot 10^{-3}$	198–338	15	32.60 ± 0.11	11.73 ± 0.04
7	28.0	273–313	9	20.39 ± 0.14	5.087 ± 0.035
8a	8.69	278–318	9	20.13 ± 0.16	5.356 ± 0.042
8b	3.75	278–313	8	20.52 ± 0.21	5.724 ± 0.058
8c	0.571	283–313	8	21.12 ± 0.20	6.463 ± 0.061
9a	2.87	278–308	7	20.83 ± 0.09	5.896 ± 0.025
9b	1.65	278–308	7	20.92 ± 0.23	6.089 ± 0.067
9c	0.180	283–323	16	22.08 ± 0.24	7.095 ± 0.076
10a	1.42	283–318	8	20.58 ± 0.09	6.032 ± 0.026
10b	0.588	283–318	8	21.17 ± 0.16	6.471 ± 0.048
10c	0.312	293–323	7	32.71 ± 0.33	10.10 ± 0.10

[a] p is determined from the concentration of the saturated N_2 stream at the temperature T . — [b] Lowest and highest temperature of the individual measurements at constant temperature. — [c] Number of individual measurements equally spaced in the temperature range given. — [d] Coefficients of the Clausius-Clapeyron equation; $\ln p = a - b \cdot 10^3/T$. — [e] p at 302 K.

for each run from the known specific heat of combustion of this contaminant ($\Delta u_c^\circ = -35804.9 \text{ J g}^{-1}$).^[38]

In Table 7, the results from typical combustion experiments are collected, along with all experimental details, while the obtained energies of combustion are listed in Table 8. The enthalpies of combustion (ΔH_c°) and the enthalpies of formation (ΔH_f°) are listed in Table 1.

Vapor Pressure Measurements – Enthalpies of Vaporization and Sublimation: A tube containing the liquid or solid compound dispersed on glass beads was submerged in a constant temperature bath (I). Nitrogen was passed at a slow, constant rate through the tube and a cooled trap (243 K). The quantity of condensed compound in the trap was measured by GC, after addition of a definite volume of a solution of an internal standard. The saturation vapor pressures p were calculated with the assumption that Dalton's law of partial pressures applied to the saturated nitrogen stream, and the small value of the residual vapor pressure at the temperature of condensation was added. The latter was derived from the linear correlation between $\ln p$ and $1/T$. It was found that the calculated values of p were independent of flow rate ($0.95\text{--}1.88 \text{ l h}^{-1}$). In Table 9, the slopes of the Clausius-Clapeyron correlations are listed, along with the range of temperatures (I) and the figures from

the individual measurements from which they were obtained. The enthalpies of vaporization and sublimation obtained therefrom are given in Table 1. The vapor pressures at 298 K are listed in Table 9; for a list of further data, see ref.^[39]

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